An Analysis of Thermoregulatory Sweating and Heat Balance in American Football Linemen and Backs

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THESIS

Submitted to the Faculty of Graduate and Postdoctoral Studies
In partial fulfillment of the requirements
for the degree of Masters of Science in Human Kinetics

School of Human Kinetics
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ACKNOWLEDGMENTS

I would like to take this opportunity to thank the following individuals for their support and guidance in the realization of this thesis and for making my years at the graduate level a memorable and unforgettable experience.

Firstly, I would like to thank my thesis supervisor, Dr. Ollie Jay, who believed in me through both the good times and the bad. Your wisdom, informal teaching style and extraordinary support gave me the opportunity to grow as both an academic and as an individual.

Dr. Glen Kenny and Dr. Gordon Robertson – Thank you for serving on my thesis committee and providing me with insightful feedback for the proper completion of my work.

Anthony Bain – Thank you for contributing the many grueling hours necessary for the completion of my data collection and for making the experience an enjoyable and memorable one.

Colleagues of the Thermal Ergonomics Laboratory – Matt Cramer, Yannick Molgat, Nicole Lesperance and Nathan Morris – Thank you for your continuous informal support and for making my experience one that I will never forget.

Participants – I would like to thank the University of South Florida Bulls football program and all those who generously volunteered to participate in my thesis work, without you this would have never been possible.

Finally, I would like to thank my family and friends – Mom, Dad, Rafal and Renée – thank you for your generous support and sticking with me through both the thick and the thin.

ABSTRACT

This thesis examined why NCAA Division 1 American football "linemen" experience greater heat strain than "backs" during summer training camps. In study #1, exercise at a heat production of 350 W/m^2 in a hot environment (T_{db}:32.4±1.0ºC; T_{wb}:26.3±0.6ºC) resulted in greater local sweating on the upper body (head, arm, shoulder and chest; all <0.05) and a greater core temperature ($P=0.033$) in linemen despite a ~25% lower heat production per unit mass (L:6.0±0.5 W/kg; B:8.2±0.8 W/kg). In study #2, greater convective and evaporative heat transfer coefficients ($P<0.05$) were found in backs during live summer training camp drills, but these did not lead to a greater dry heat transfer or evaporative capacity. However, the maximum metabolic rate per unit mass was lower in linemen due to differences surface area-to-mass ratio. In conclusion, the greater heat strain previously reported in linemen likely arises, in part, from differences in sweating efficiency and body morphology.

PART ONE: EMPIRICAL AND THEORETICAL CONSIDERATIONS

CHAPTER 1: INTRODUCTION

1.1 Background

Humans are homeotherms and therefore maintain their body temperature (core) at ~37°C in order to sustain optimal conditions for key physiological and chemical processes [1] in changing thermal environments. A rise in core temperature of only 1 to 2°C above this "set point" temperature can limit work performance [2] and places the body at a greater risk of physiological heat strain and heat illnesses. At the onset of exercise, metabolic heat production is immediately elevated since heat is a by-product of fuel metabolism within muscles (thermogenesis) [3]. Heat production during maximal exercise can be more than 10 times greater than at rest, and if no thermoregulatory mechanisms were present, core temperatures would rise at a rate of ~1ºC every 5-min [4]. In contrast to thermogenesis, the rate of heat dissipation to the ambient environment (thermolysis) changes much slower with a slight delay after the onset of exercise followed by an exponential increase [5, 6]. This dissociation between the onset of thermogenesis and thermolysis results in a positive rate of heat storage and subsequent rise in core temperature. In environments where heat loss avenues (e.g. evaporation, convection/conduction) can be sufficiently pronounced to match the rate of thermogenesis via physiological responses (e.g. sweating, vasodilatation) the body will once again achieve heat balance with a new elevated steady state core temperature (compensable heat stress) reached after ~45-min. However, particular combinations of environmental parameters (air temperature, mean radiant temperature, relative humidity & air velocity) and personal parameters (clothing and activity) result in a consistent mismatch between thermogenesis and thermolysis throughout exercise (uncompensable heat stress). Under such circumstances a continually positive rate of heat storage would occur leading to unchecked increases in core temperature [1] and eventually heat-related health problems.

Heat stroke is the most commonly known heat illness; however heat illnesses can be stratified into 5 key categories of varying severity: heat rash, heat cramps, heat syncope, heat exhaustion and heat stroke [1]. Table 1 provides a synopsis of key symptoms and the primary physiological disturbances of each condition while experiencing exercise-induced hyperthermia.

Table 1. Classification (symptoms, core temperature and physiological cause) and stratification of several heat illnesses caused by exercised-induced hyperthermia.

Category	Symptoms	Core Temp (°C)	Physiological Disturbance
Heat Rash	Blister like vesicles giving off a pricking sensation during heat exposure	>38°C	Inflammation due to blocked sweat glands and retention of sweat.
Heat Cramps	Painful muscle spasms typically occurring during work	>37.5°C	A loss of body salt due to excessive sweating.
Heat Syncope	Fatigue, headache, pale and clammy skin	>38°C	Pooling of blood due to vasodilated blood vessels
Heat Exhaustion	Dry red and hot skin, erratic breathing, high HR and eventual death	>38°C	Dehydration, decrease in blood volume
Heat Stroke	Dry red and hot skin, erratic breathing, high HR and eventual death	>40°C	Failure of the central drive for sweating leading to uncontrolled rises in core temperature

The prevalence of heat stress and heat illnesses within sporting teams and sports organizations has become a growing concern over the past few decades. Athletes participating in American as well as Canadian football during the summer months are particularly at risk due to the high ambient temperatures, the intensity of the sport [7] and the type of equipment worn (high thermal resistance) [8, 9]. The issue has been brought to the forefront in the past decade with high profile cases reaching mainstream news such as that of NFL player Korey Stringer who collapsed and died from exertional heat stroke in August of 2001 during an NFL preseason training camp. Stringer was admitted into hospital with a core temperature over 42°C.

The health risks associated with this summer football activities are highlighted not only by the death of Korey Stringer but by the large number of heat-related deaths across all levels of competition; professional, college and youth/minor [7]. Though athletic associations have focused their efforts on addressing the issue by implementing and promoting preventative measures and policies such as the National Collegiate Athletic Association (Proposal 2002-84) mandatory heat acclimation protocol (2002) [10], the prevalence of heat related deaths continues to be a concern. For example, a total of 123 high school football players died of heat-related illnesses between 1960 and 2009, with the death rate more than doubling in the past 15 years [11].

The majority of these fatalities occurred at the start of preseason during training camp [12] when players compete for a position on a professional or college team, or even a competitive team in youth football. This in turn promotes an environment that leads players to ignore warning signs related to heat illnesses [7, 9] and places them at risk for heat stroke or even death. Figure 1 shows the high average ambient temperatures across the continental United States in the month of August, the month in which most training camps take place. It is clear that irrespective of where training camps are held, ambient conditions in all parts of the United States are sufficiently high to pose a danger to football players.

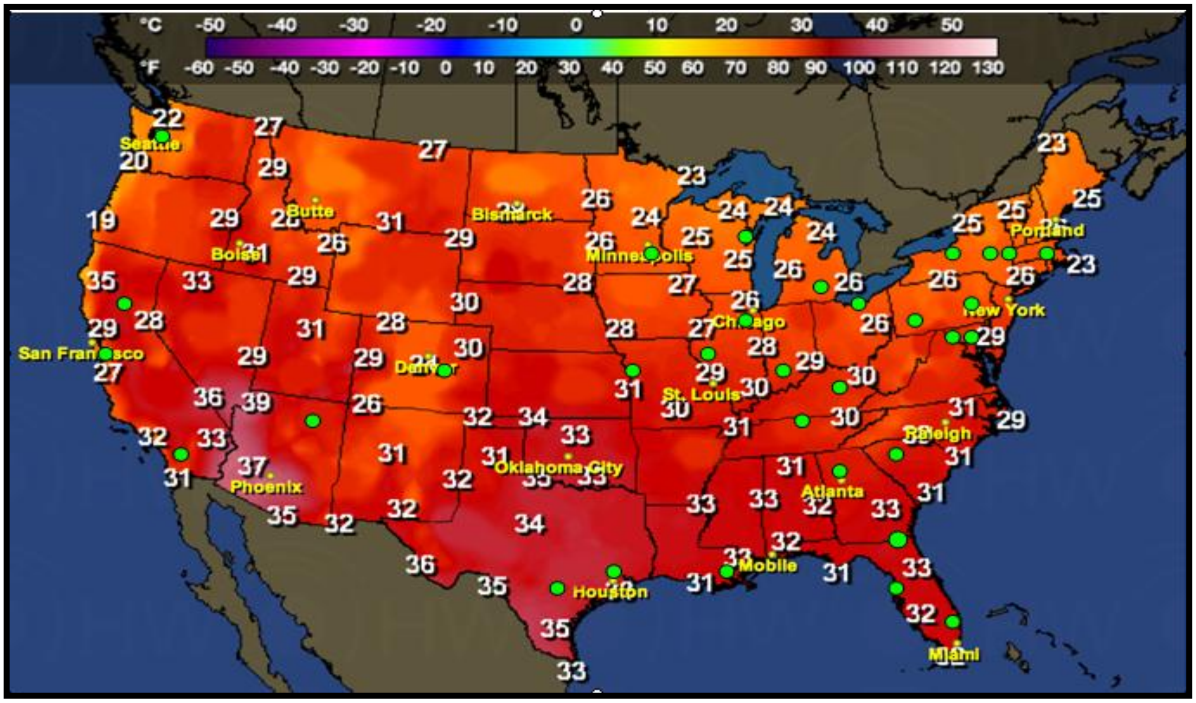

Figure 1. Mean temperature highs (in °C) in the United States for August 2009 with a visual representation of all 32 NFL training camp locations (Green dots).

In order to help prevent heat-related health problems among these athletes, an understanding of the factors determining a player's heat stress response (i.e. magnitude of core temperature elevation) is needed. On any given day of training camp, the source of individual variation in core temperature response is not likely to be due to environmental factors since all players will be exposed to the same ambient conditions. Rather, individual factors such as body mass, metabolic heat production and sweating efficiency will likely be the primary determinants. Recent work by Godek *et. al.* demonstrated that larger players (linemen) are in fact more susceptible to heat illnesses as they show much larger increases in core temperature during an NFL training camp practice when compared to smaller players (backs) [13]. Previous literature has also suggested that an individual's heat stress response may be largely dependent on body morphology [14-16]. This has large implications when considering the sport of American football due to the large amount of morphological variation seen among different positional groups [17-22]. Compared to backs, linemen exhibit a larger body mass and a greater body surface area (BSA) [23, 24] and it is likely that these differences in morphology will increase the susceptibility of linemen to heat illnesses [14-16, 25]. Firstly, for a given task, a greater total body mass would increase metabolic rate and subsequently metabolic heat production, resulting in a greater heat storage [26, 27]. Furthermore, it has been shown that the density of sweat glands decreases linearly with increasing BSA [28]. As such, the higher BSA and potentially lower sweat gland density in linemen may result in reduced ability to completely cover the skin by secreted sweat (maximum skin wettedness) thereby decreasing the maximum rate of evaporation possible in the given environment (E_{max}). Additionally, linemen exhibit a decreased BSA-to-mass ratio which would reduce their physical interface with the ambient environment relative to their thermogenic mass [27].

Most research has attributed the greater core temperatures observed in linemen to greater whole body sweat rates that could not be maintained due to increasing levels of dehydration [13, 20, 29]. While marked dehydration may exacerbate heat stress [12] differences in hydration status typically shown in linemen and backs ($\leq$ -1.5%) did not correlate significantly with the magnitude of core temperature elevation [13]. In fact, the aforementioned study showed that linemen were actually less dehydrated (measured by urine specific gravity), despite showing greater core temperature elevations compared to backs [13] and higher whole body sweat rates [30]. Furthermore, in non-football playing populations it has been shown that metabolic rate and not percent dehydration is a better predictor of rectal temperature (core temperature) [15, 31]. This demonstrates that hydration status alone is not a valid predictor of heat stress as even euhydrated individuals may experience significant heat stress if heat production exceeds the body's ability to lose heat to the external environment.

Moreover, core temperature differences between linemen and backs have also been hypothesized to be a result of differences in self-generated air velocities between the two position groups [26]. Lineman-specific position drills tend to be more static in nature while back-specific drills tend to be more sprint based requiring the player to cover large amounts of the field each play in the shortest time possible resulting in a potentially lower attendant convective and evaporative heat transfer in the less mobile players (linemen).

1.2 Rationale

To date, little is known about the primary causes for the higher core temperatures seen in linemen compared to backs. Specifically, it remains unclear if these position-related differences in heat strain are due to physical and/or physiological limitations to heat dissipation in "linemen" compared to football "backs". In order to address this question, 1) heat loss responses in elite football linemen and backs need to be compared at a fixed metabolic heat production in a controlled climate; and, 2) heat loss potential need to be compared between linemen and backs during live preseason training camps.

1.3 Objectives

The primary objectives of this thesis are to:

A) Investigate whether differences in regional upper body sweat rates between football linemen and backs exist independently of differences in metabolic heat production.

B) Investigate the interaction of on-field self-generated air velocities, mean skin temperatures and ambient conditions on heat balance parameters (convective and evaporative heat loss potential) between linemen and backs during a series of summer training camp practices.

1.4 Hypotheses

A) At the same metabolic heat production per unit BSA, significantly greater sweating and core temperatures would still be observed in larger linemen relative to smaller backs indicating a lower evaporative efficiency in linemen.

B) During typical preseason summer training camp, significantly greater self-generated air velocities would be observed in backs compared to linemen. Consequently, a significantly greater heat transfer coefficient for convection (h_c) and evaporation (h_e) would be observed in backs despite similar mean skin temperatures. However, after accounting for differences in body surface area-to-mass ratio, the maximum metabolic rate per unit mass (W/kg) that is physiologically compensable would be significantly lower in linemen relative to backs.

1.5 Relevance

This study will help advance our understanding of how American football athletes interact with their thermal environment. More specifically, it will attempt to isolate the determinants of the previously observed differences in core temperature elevations during a typical practice between linemen and backs. This information could ultimately lead to the creation of more effective on-field interventions that could potentially be individualized to particular players or position groups.

1.6 Limitations

The results of these experiments will not be generalized to the entire general population; volunteers will be well-trained, male, NCAA Division 1 athletes with no identified health problems. Subjects will be limited to a upper core temperature of 39.5°C (i.e. gastric). As such, the results of the study will not be generalized to those suffering severe hyperthermia (>40°C; gastric). Finally, during the first investigation, the prescribed exercise protocol will be continuous in nature to ensure a fixed metabolic heat production per unit of surface area. This will limit the ability to generalize these findings to on-field training camp activities as most consist of intermittent rather than continuous exercise.

1.7 Assumptions

A euhydrated state will be assumed, due in part to an administered pre-testing bolus of water and on-field fluid availability. However, no direct measure of hydration will be taken. Furthermore, heat acclimation status will be assumed equal between both linemen and backs, as all athletes are required to take part in summer conditioning workouts prior to the start of training camp.

CHAPTER 2: REVIEW OF THE LITERATURE

2.1 Thermoregulatory Control

The ability to maintain and protect a constant body temperature ~37.0±0.5°C regardless of large variations in environmental conditions requires a complex interaction between the central nervous system, the cardiovascular system and the body's skin [32, 33]. The "set-point" theory of temperature regulation is explained as a closed-loop feedback regulator [33-35], which assumes that deep core temperature is by some means compared to a reference temperature. With a rise in body temperature, both central and peripheral thermoreceptors send signals to the pre-optic/anterior hypothalamus (integrator) with information about the body's thermal status [36]. Peripheral thermoreceptors are located below the skin surface within the dermis detecting both temperature changes in the body's "shell" [37, 38]. Central thermoreceptors located within the central nervous system detect changes in the body's "core" temperature [35]. Thermal signals from both of these thermoreceptors (sensors) are then integrated at the hypothalamus and compared to a central reference temperature. When this temperature deviates away from the set-point, afferent feedback is used to initiate and modulate the necessary thermoeffector responses of eccrine sweating and vasodilatation in the heat as well as shivering and vasoconstriction in the cold [37]. The relative contribution of "core" and "shell" thermoreceptors to the observed thermoeffector responses are 90/10 in the heat and 67/33 in the cold [39].

As core temperature rises the sympathetic nervous system is first to respond by vasodilating the subcutaneous vascular bed which in turn increases blood flow to the skin surface [3]. This allows for the dispersion of stored body heat over a greater surface area and promotes a greater rate of heat loss through radiation and convection by virtue of a pronounced temperature gradient between the skin and the ambient environment. After an increase in core temperature of approximately ~0.2 to 0.3°C above resting value the sweat response is initiated [40].

Although the "set point" theory is often the most widely accepted, the exact control mechanism of human thermoregulation is still widely debated. In contrast to set point theory it has been suggested that a strictly defended hypothalamic core temperature does not determine thermoregulatory effector responses, rather these responses are regulated by the body's drive to attain heat balance [41, 42]. Since the body's metabolic heat production is in a constant state of flux, rather than a defended core temperature the body responds to both the inflow and outflow of heat with a dynamic effector response to achieve heat balance. Despite the control of thermoregulatory responses remaining a topic for debate, it is clear that irrespective of control processes, the body effectively regulates physiological heat loss responses to elicit a rate of net heat dissipation equal to that needed for heat balance.

2.2 Time Course of Thermogenesis and Thermolysis

At the onset of physical activity there is an almost instant rise in the rate of thermogenesis due to the liberation of energy from the body's key metabolic systems [43]. In order to supply this energy, cells generate ATP (Adenosine triphosphate) through three different processes or systems: the ATP-PCr (phoshocreatine) system, the glycolytic system and the oxidative system. Initial energy requirements (1-2 min) are supplied by the ATP-PCr system (3-15 s) and anaerobic glycolysis (1-2 min). Both of these reactions are anaerobic and therefore do not require oxygen in order to produce energy. The primary limitation of the anaerobic system is a build up of lactic acid, resulting in an acidification of muscle fibers effectively shutting off glycogen breakdown and interfering with actin-myosin cross-bridging thus halting continued physical activity [44].

If oxygen is present, the oxidative system becomes the primary energy system. Unlike the first two systems (ATP-PCR & anaerobic glycolysis) the oxidative system has tremendous energy-yielding potential (36-38 ATP per molecule of glucose) and is therefore the primary focus when considering any activity lasting longer than 1-min.

In contrast to thermogenesis, thermolysis (heat loss) does not respond instantly following the onset of exercise. Typically a delay of approximately ~5 min [5, 6] is observed before an exponential increase in thermolysis occurs. Heat production at the early stages of exercise is stored primarily in the active muscles resulting in an increase in muscle temperature [4]. As muscle temperature rises, an increase in sympathetic activity resulting in a redistribution of blood from the periphery to the working muscles allows for a greater convective heat exchange between the muscles and the blood [3]. As exercise continues the increase in blood flow through the muscle capillary bed along with conductive heat transfer to adjacent organs will redistribute metabolic heat to the core initiating an increase in vasodilation and skin blood flow [45]. The dissociation between thermogenesis and thermolysis results in a positive rate of body heat storage (+S) and subsequently rise in core temperature that for a given S is determined by body mass and body composition. In situations that promote the loss of heat from the body to the external environment the combination of all physiological heat loss mechanisms can elicit a sufficiently large thermolytic response to match the rate of thermogenesis after approximately 45 min of continuous exercise allowing for core temperature to reach a new elevated steady state [46]. It is important to note that the newly achieved steady-state core temperature is not representative of a failure on the part of the thermoregulatory system but is caused by the initial lag in thermolysis following the onset of exercise.

American football related activities in a preseason summer training camp typically present a combination of intense bouts of exercise, hot and humid environments, and thermally resistant protective equipment [8, 47]; and likely lead to prolonged periods of imbalance between thermogenesis and thermolysis. Such a scenario would result in a positive rate of heat storage and a marked rise in core temperature [26], which if left unchecked would lead to an increased risk of heat-related illnesses.

2.3 Basic Heat Balance Equation

The dynamic balance between heat production and net heat loss to the environment is represented by the conceptual heat balance equation [1]:

$$M - W = (\pm K \pm C \pm R + E) \pm S$$

Where:

M = Rate of Metabolic Heat Production (W/m^2)
W = Rate of External Mechanical Work (W/m^2)
K = Rate of Conductive Heat Loss / Gain (W/m^2)
C = Rate of Convective Heat Loss / Gain (W/m^2)
R = Rate of Radiative Heat Loss / Gain (W/m^2)
E = Rate of Evaporative Heat Loss (W/m^2)
S = Rate of Body Heat Storage (W/m^2)

The heat balance equation is separated into three key components: those that define the rate at which heat is generated within the body (M-W), the rate of net heat exchange with the environment (±K ±C ±R +E), and the rate at which heat is stored within the body (±S).

2.4 Metabolic Heat Production (M-W)

Metabolic heat production consists of two components; metabolic energy expenditure (*M*) and external work (*W*).

All reactions taking place in the body require energy. To fuel these reactions humans extract oxygen from inhaled air and ingest carbohydrates, fats and proteins in the form of food. The amount of energy derived from using 1 L of O_2 to oxidize carbohydrates equals 21.13 kJ while fats yield 19.62 kJ. In order to calculate total metabolic heat production, total energy expenditure must first be calculated using (Equation 1) (oxidative system) [48]:

$$M \equiv VO_2 \frac{\left(\frac{RER-0.7}{0.3}e_c\right)+\left(\frac{1-RER}{0.3}e_f\right)}{60\times BSA}\times 1000 \text{ W/m}^2 \quad (1)$$

Where:

VO_2 = Absolute Oxygen Consumption (L/min)
RER = Respiratory Exchange Ratio (VCO_2/VO_2)
e_c = energy equivalent of carbohydrates (21.13 kJ per L of O_2)
e_f = energy equivalent of fats (19.62 kJ per L of O_2)
BSA= body surface area (m^2)

The energy yielded from metabolic reactions is available for the body to use towards mechanical work. Most reactions occurring in the human body are quite inefficient as energy produced by the body is primarily released as heat while some of it, (no more than 30%) will be converted to do mechanical work [1]. Mechanical efficiency is therefore expressed as a percentage, representing the ratio of energy input to work output [49]. The ideal efficiency for every movement would be 100% however mechanical efficiency for human locomotion ranges anywhere from 1% (swimming) to 30% (cycling). For example, if a task is 30% efficient (e.g. cycling), a 500 W energy expenditure (*M*) will produce 150 W external work (*W*) and 350 W metabolic heat production (*M-W*); whereas for one that is 1% efficient (e.g. swimming), 500 W will produce 5 W of external work and 495 W of heat. However, external work during an American football practice would have to be assumed as zero due to players primarily running along a horizontal terrain (22).

American football presents many constraints (i.e. full body contact and intermittent drills) to the accurate measure of on-field metabolic heat production. As such, one of the largest limitations in understanding differences in core temperature elevations between position groups is the valid estimation of the energy cost of a football practice or training camp due to limited research quantifying the energy expenditure and metabolic heat production by American football players. Moreover, a comparison of the actual metabolic requirements of various position groups has yet to be done. Since it has been established that metabolic heat production is the best predictor of core temperature elevation [15, 31], this information is necessary to understand the metabolic load imposed by the sport itself, the stress it places on both the wet and dry heat loss mechanisms and how it contributes to the rate of heat storage and subsequent increases in core temperature for different position groups as previously shown in the literature [26]. Furthermore this information could then be used to establishing which football activities result in the largest metabolic strain giving coaches and trainers additional resources when planning pre season practices.

2.5 Conduction (K)

Conduction represents a transfer of heat between two solid surfaces in direct contact with one another. As stated by the second law of thermodynamics, heat flows spontaneously from a hot body to a cold one but not the reverse [1]. This process is described by Equation 2:

$K = h_k(T_{sk} - T_{surface})$……………………………….(W/m^2)…………………………….(2)

Where:

h_k = Thermal conductivity of the material in contact with the body (W/(m•°C))
T_{sk} = Weighted mean skin temperature (°C)
$T_{surface}$ = Surface temperature of conducting material (°C)

As an object such as a human hand touches a warmer object such as a heated frying pan, heat is transferred through conduction from the pan into the hand. The temperature gradient (T_{sk}-$T_{surface}$) between the two objects is the driving factor for conduction to continue. Furthermore, the thermal conductivity or insulative properties of the material through which heat is being conducted must also be considered. These values can often be found in databases (Table 2) specifically quantifying heat exchange in various mediums [47]. However, when considering whole-body heat balance, conductive heat loss is often assumed to be negligible (i.e. K ~ 0).

Table 2: Typical values of thermal conductivity for solids, liquids and gases [50].

Substance	Temp (°C)	Thermal Conductivity (W/(m•°C))
Solids		
Silver (pure)	0	417
Copper (pure)	0	356
Aluminum (pure)	0	228
Iron (pure)	0	73.7
Liquids		
Water	0	0.57
Blood	37	0.51-0.53
Gases		
Hydrogen	0	0.168
Air	0	0.024
Oxygen	0	0.015
Carbon dioxide	0	0.015

In the case of American football, the helmet and pads of a typical uniform cover ~50% of the body surface area, while the remaining equipment (i.e. pants, socks) covers an extra 20% [9]. This provides a large interface for heat transfer between the skin and in this case protective padding (conductive medium). As such, skin temperature in a warm environment, would be greater than that of equipment, eliciting a heat transfer from the skin to the equipment. However, the temperature gradient should decrease and reach equilibrium quickly after the player puts on the uniform. The gradient once equalized would remain small due to the insulative properties of football padding [47] thereby reducing the potential for conductive heat loss [8]. Conductive heat loss in American football can therefore be considered negligible within the context of the whole-body heat balance equation.

2.6 Convection (C)

The transfer of heat energy between the body surface and air at different temperatures through the movement of intermediate substance (i.e. air) is known as convection. This process is described by Equation 3:

$C = f_{cl} h_c (t_{cl} - t_{db})$ ……………………………….(W/m^2)……………………….……....(3)

Where:

f_{cl} = clothing area factor.
h_c = convective heat transfer coefficient (W/(m^2•K))
t_{cl} = mean temperature over the clothed body (°C)
t_a = air temperature (°C)

When core temperature begins to rise above resting levels an increase in blood flow is observed presenting a divergence of heat stored in the core towards the periphery, which then creates a temperature gradient between the ambient environment and the skin surface. Convection can occur by two separate means; natural or forced. Natural convection is a product of the buoyancy forces resulting from differences in air temperature (e.g. hot air rising). Forced convection on the other hand is due to an increase in airflow thereby creating a larger displacement of air by any other supplementary mechanical means (e.g. mechanical fan or sprinting).

The ability to dissipate heat through convection is largely dependent on the amount of air flow present. Although players will be subjected to the same environmental air velocity on the field during training camp, the demands placed on various positional groups are inherently different. Offensive and defensive linemen are typically more static on the field when compared to their more mobile teammates (backs and receivers) [13, 20]. Common drills for larger players involve blocking and pushing exercises with limited physical displacement while smaller players tend to perform more sprint oriented drills [26]. This would have large implications on the amount of self-generated air velocity and consequently the maximum amount of convective heat loss that could occur by virtue of changes in the convective heat transfer coefficient. Adams et. al. showed that in an environment of ~35ºC participants that exercised in still air conditions (<0.2 m/s) experienced higher core temperatures and generated higher sweat rates when compared to those who exercised with a facing wind speed of 3 m/s [38]. However, due to the curvilinear relationship between air velocity and h_c ($h_c = 8.3v^{0.6}$) [51], the largest increase in h_c occurs at air velocities between 0.2 and 1.0 m/s. As such even with the potentially large differences in running speeds between position groups, these may not be sufficient to generate significant differences in the convective heat transfer coefficient by virtue of all players being at the upper end of this curvilinear relationship. To date there has been no attempt to quantify convective heat loss by concurrently measuring player movement speed and mean skin temperature during preseason summer training camp practices.

2.7 Radiation (R)

All bodies above a temperature of absolute zero emit thermal radiation. This heat transfer occurs in the form of electro-magnetic waves between objects of varying temperatures [1] and is described by equation 4:

$R = h_r(T_{sk} - T_r)$ ……………………………….(W/m^2)……………………..………...(4)

Where :

h_r = radiative heat transfer coefficient (W/(m^2•K))
T_{sk} or T_{cl} (in the case of a fully clothed individual) = skin temperature (°C)
t_r = mean radiant temperature (measured by black globe thermometer) (°C)

The human body constantly radiates heat from its surface in all directions to other bodies around it, but it can also receive radiative heat from those same objects. If the temperature of the objects around an individual is greater than skin temperature the human body will experience a net heat gain through radiation. The most common example of this type of gain would be radiative heating from exposure to the sun. The amount of heat transferred through radiation is dependent on the orientation of the body relative to the heat source, the temperature of the objects and the movement of the heat source in relation to the body. The closer and warmer the radiative object is to the body the greater the energy transfer. When considering athletes participating in on field practice during summer training camp peak levels of solar radiation would occur between 11 am and 1 pm [50]. This would have large implications in scheduling football practices during training camp as coach and trainers should avoid exposing players to times of peak solar radiation. Most teams acknowledge this danger and practices are usually scheduled in the early morning or late afternoon when solar radiation is reduced.

While most research reports environmental conditions on the field during American football practice, radiation is often omitted [13, 18, 20, 29]. An accurate measurement of mean radiant temperature is a key requirement for the analysis of human heat balance [52]. The football field presents an environment where both direct and diffuse solar radiation can impact thermal comfort, perceived outdoor temperature and thermal status [53].

2.8 Evaporation (E)

Evaporation is the primary avenue for heat dissipation when exercising in a warm environment. In hot, dry conditions, where the skin to air temperature gradient is small, evaporation may account for as much as 98% of the dissipated heat. Any factor that limits evaporation (i.e. high humidity, dehydration, surface area restrictions) will therefore have profound effects on the risk for heat illness in the exercising athlete [2, 15, 16, 54]. Evaporation is calculated using equation 5:

$$E = \frac{w(P_{sk,s} - P_a)}{\left(R_{e,cl} + \left(\frac{1}{f_{cl} h_e}\right)\right)} \ldots\ldots (W/m^2) \ldots\ldots (5)$$

Where:

P_a = water vapour pressure in the ambient air (kPa)
$P_{sk,s}$ = Water vapour pressure at the skin, normally assumed to be that of saturated water vapour at skin temperature (kPa).
$R_{e,cl}$ = evaporative heat transfer resistance of the clothing layer (m^2/(kPa•W))
h_e = evaporative heat transfer coefficient (W/(m^2•kPa))
w = skin wettedness (Gagge, 1937). The fraction of wet skin (ND)

Evaporative heat loss is in an absolute sense determined by the partial pressure gradient between sweat on the skin and the water in the ambient air (humidity). Evaporation will occur if there is a lower partial pressure in the ambient air when compared to that of the skin. The evaporation of 1 gram of sweat removes 580 kcal or 2426 kJ of heat energy [43].

Elevations in local skin temperature and core temperature independently elicit sweat production [54]. In general, sweat gland density and sweat output per gland differs from one region of the body to the next. Kondo *et. al.* (1998) measured sweat rates on the forehead, forearm, chest, back and thigh showing differences in both the number of active sweat glands (ASG) and individual sweat gland output (SGO) with varying workloads (35% VO_{2max}, 50%

VO_{2max} and 65% VO_{2Max}) [55]. Their data showed that the region with the highest density of ASG was the forehead (~145-200 glands cm^2) at all work intensities while the lowest was chest (~55-60 glands cm^2). Furthermore, SGO showed the reverse pattern of ASG with the largest outputs seen on the chest (~9-15 μg gland/min) and lowest on the forehead (~4-10 μg gland/min). By the age of two, the number of sweat glands covering the human body has already been established [56]. As such, a greater BSA will likely result in the distention of the skin subsequently causing a decrease in sweat gland density (SGD) in larger individuals [28]. With a lower SGD, the distance to neighboring sweat glands would be greater and therefore could potentially decrease the total skin surface area that could be covered with secreted sweat thereby decreasing sweating efficiency. The theoretical sweating efficiency can be estimated by the ratio of evaporation required for heat balance (E_{req}) and the maximal evaporation possible in the given environment (E_{max}). Candas et al. [57] found that a decline in sweating efficiency begins in humans when skin wettedness (E_{req}/E_{max} ratio) reaches values of approximately 0.70. With a lower sweat gland density and subsequently lower theoretical maximum skin wettedness likely seen in larger individuals, the maximum rate of evaporation (E_{max}) at a given evaporation required for heat balance (E_{req}) would be lower resulting in a lower sweating efficiency. Bain et al. [58] recently demonstrated that as the E_{req}/E_{max} ratio increases, local sweat rate measured on the forehead and forearm increases in parallel, presumably due to a reduction in sweating efficiency [57]. As such, larger individuals (i.e. larger BSA) may experience greater sweat rates secondary to their lower SGD. A convective current would help promote a greater evaporation by increasing the evaporative heat transfer coefficient through the Lewis relation [50], therefore increasing sweating efficiency by increasing E_{max} for a given E_{req} thereby reducing the E_{req}/E_{max} ratio. As such, an understanding of differences in positional self-generated convective currents will also provide a more complete understanding of differences in the maximal rate of evaporation between linemen and backs.

The typical American football team has a wide range of morphological variations between its players and positions. An understanding of the interplay between sweat rates and player types will allow teams to further assess the extent to which certain players may be more susceptible to heat stress and concurrent illnesses. Larger players theoretically have a greater capacity to store larger amounts of heat due to their increase in body size [16]. With a larger heat sink (linemen) a larger heat storage would be required to raise core temperature by 1ºC compared to a smaller player. Therefore for the same amount of heat storage, linemen would have a smaller increase in core temperature.

2.9 Individual factors influencing heat balance during exercise

2.9.1 Hydration

The human body is largely made up of water (approx. 60%) that is contained in three distinct compartments: intracellular (up to 67% of total water content) and extracellular which can be further separated into intravascular or blood plasma (8%) and interstitial water content (25%) [50]. However, these values will vary, as the distribution of the body's body water content is dynamic in nature due to the semi-permeable properties of cell membranes, which allow water to flow between compartments by virtue of differences in osmotic pressure [59]. A reduction in body water content equivalent to approx 2% of total body mass has been linked to a decrease in exercise performance [60] and is often the standard when classifying dehydration. When an individual becomes dehydrated less water content is present in the blood plasma (intravascular content) therefore decreasing blood plasma volume (hypovelemia). This hypovolemic condition will decrease the osmotic pressure, subsequently limiting fluid movement between compartments thereby decreasing the amount of water content available to the sweat gland and the amount of blood being circulated to the periphery (skin surface) [61]. Fluid losses typical of American football training camps have been shown to be mild <2% of total body mass [10, 62]. This is likely due to proactive strategies currently in place at all levels of football competition. As such, levels of hydration in American football linemen and backs have not been shown to correlate with increases in core temperature [26]. In fact, this particular study demonstrated larger elevations in core temperature in the linemen who were in fact more hydrated than the backs. As such, while dehydration presents inherent risks to players exercising in the heat and should not be ignored, a more encompassing approach must be used when attempting to isolate the primary determinants of core temperature elevations in these athletes.

2.9.2 Adiposity

American football linemen demonstrate a much greater body fat percentage when compared to backs [63]. This greater adiposity may potentially contribute to the previously observed larger core temperature increases in this position group when compared to backs. Fat tissue presents a lower specific heat capacity (2.9 kJ/(kg•°C)) compared to fat free mass (3.6 kJ/(kg•°C)) [64] and would therefore yield a lower average specific heat of the body in the linemen when compared to the backs. It follows that if a given amount of heat were stored in the body, the lower specific heat capacity of the linemen would theoretically produce a slightly greater increase in core temperature. Furthermore, while it may be argued that a greater adiposity, acting as an insulator, may contribute to lower skin temperatures and therefore a reduction in the potential for heat dissipation through both dry and evaporative heat loss avenues [25], it is likely that any insulative fat layers are by-passed by blood flow after the onset of exercise [14, 15] therefore not impeding heat exchange at the skin surface.

2.9.3 Aerobic Fitness

On most American football teams aerobic fitness is likely lower in linemen relative to backs [65] and there is no doubt that an increase in aerobic fitness facilitates a greater maximum sweat rate. Sato and Sato [66] reported that isolated sweat glands taken from individuals who described themselves as fit were larger than those in unfit individuals. Furthermore, it has been shown that physical training (fit individuals) results in improved secretory activity by virtue of an increased cholinergenic sensitivity at the level of the gland [66, 67]. However, greater whole body sweating has been previously observed in linemen, who are likely less fit [30]. Furthermore both sub-maximal whole-body [68-70] and local sweat rates [58] are primarily determined by metabolic heat production per unit surface area. As such, any differences in sweat rates between linemen and backs must examined when employing the same metabolic heat production per unit surface area rather than an exercise intensity relative to an individual's aerobic fitness.

2.9.4 Clothing - The American Football Uniform

The American football uniform presents a large physiological heat stress reducing both dry (convective) and evaporative heat loss. The helmet and pads of a typical uniform cover ~50% of the skin surface, while the remaining equipment (i.e. pants, socks) covers an extra ~20% [9]. This equates to ~70% of the football player's body being covered and not exposed to the ambient environment. This additional equipment increases the surface area available for heat transfer and this can be quantified by f_{cl} (clothing area factor) as the ratio between the clothed surface area of the body to the nude surface area [1]. However, this increased surface does not translate into an increased evaporative and convective heat loss potential due to the thermal and evaporative resistance of a typical football equipment configuration [8, 9, 47].

McCullough and Kenney (2003) were the first to quantify the thermal and evaporative resistance of several American football uniform configurations using a whole-body thermal manikin [47]. A typical warm weather equipment configuration used during summer training camps is usually comprised of a helmet, shoulder pads, short sleeve mesh jersey, jock strap, girdle, leg pads (hip thigh, and tailbone), football pants, ankle socks and turf shoes. This type of configuration presented a thermal resistance of 0.199 m^2•°C/W) compared to a reference configuration (shorts and t-shirt) of 0.140 m^2•°C/W - a difference of almost 30% in whole body thermal resistance. Similarly, the warm weather configurations also showed an evaporative resistance of 0.032 m^2•kPa/W compared to the reference uniform of 0.020 m^2•kPa/W, a difference of ~63% in whole body evaporative resistance.

The thermal resistance of clothing will influence t_{cl} (mean temperature over the clothed body (°C)). As thermal resistance increases a decreased amount of heat is transferred from the shell (skin) to the outer layer of clothing, thus decreasing t_{cl}. The temperature gradient between the clothing surface and the ambient air will therefore become smaller reducing the rate of convective heat loss [8, 9]. Evaporative heat loss would also be affected by the evaporative resistance of the equipment. An increase in resistance would decrease the ability for moisture to leave the microclimate between the skin and equipment decreasing the sweating efficiency of the athlete by not allowing for sweat to be evaporated at the outer surface of the uniform. American football presents a unique situation in which it is known that the equipment used poses a heat stress risk to athletes however the nature of the sport does not allow for large amounts of flexibility as the potential for injury is high.

PART TWO: METHODS AND RESULTS OF THE THESIS

STUDY #1: Sweating is greater in NCAA football linemen independently of metabolic heat production

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Published in Medicine and Science in Sports and Exercise (Accepted, July 5th, 2011)
MSSE-D-11-00292R2 (Epub ahead of print)
DOI: 10.1249/MSS.0b013e31822cb4e2

This research was supported by a NFL Charities Medical Research Grant.

Running Title: "Regional sweating in American football"

ABSTRACT.

Purpose: To investigate whether differences in local sweat rates on the upper body between American football linemen (L) and backs (B) exist independently of differences in metabolic heat production. **Methods:** Twelve NCAA Division 1 American football players (6 linemen [mass: 141.6±6.5 kg; body surface area (BSA): 2.67±0.08 m^2] and 6 backs [mass: 88.1±13.4 kg; BSA: 2.11±0.19 m^2]) cycled at a fixed metabolic heat production per unit BSA of 350 W/m^2 for 60-min in a climatic chamber (T_{db}:32.4±1.0ºC; T_{wb}:26.3±0.6ºC; v:0.9±0.1 m/s). Local sweat rates (LSR) on the head, arm, shoulder, lower back and chest were measured after 10, 30 and 50-min of exercise. Core temperature (T_{core}), mean skin temperature (T_{sk}) and heart rate (HR) were measured throughout exercise. **Results:** Since metabolic heat production per unit surface area was fixed between participants, the rate of evaporation required for heat balance was also similar (L:261±35 W/m^2; B:294±30 W/m^2; P=0.11). However, LSR on the head, arm, shoulder and chest were all significantly greater (P<0.05) in linemen at all time points, and end-exercise T_{core} was significantly greater (P=0.033) in linemen (38.5±0.4ºC) relative to backs (38.0±0.2ºC) despite a ~25% lower heat production per unit mass. The change in T_{sk} from rest was greater in linemen (P<0.001) after 15, 30, 45 and 60-min and HR was greater in linemen for the last 30-min of exercise. **Conclusion:** Football linemen sweat significantly more on the torso and head than football backs independently of any differences in metabolic heat production per unit BSA and therefore the evaporative requirements for heat balance. Despite greater sweating, linemen demonstrated significantly greater elevations in core temperature suggesting that sweating efficiency (i.e. the proportion of sweat that evaporates) was much lower in linemen.

Keywords: Core temperature; Football training camps; Heat stress; Heat dissipation; Hyperthermia; Thermoregulation

INTRODUCTION

Paragraph Number 1 Heat stress has become a primary concern among sports organizations over the past couple of decades. Athletes participating in American football training camps during the summer months are at a particular risk of physiological heat strain due to high ambient temperatures and humidity, the metabolic demands of the sport [7] and the thermal resistance of the equipment worn [8, 9]. Since 1995, thirty-nine athletes have died of heat related illnesses while participating in the sport at both the amateur and professional levels of competition [71].

Paragraph Number 2 Athletes participating in American football typically represent a wide range of morphological variation when compared to other popular summer sports (e.g. running, cycling or soccer) [72]. Vast differences in physical characteristics such as total body mass, body surface area (BSA), percentage of body fat and surface area-to-mass ratio may potentially predispose some groups of players to a greater risk of critically high core temperatures [14-16, 25]. Indeed, a recent study by Godek *et al.* demonstrated that larger "linemen" such as offensive linemen, defensive tackles and defensive ends had significantly larger elevations in core temperature during an NFL training camp relative to smaller "backs" such as defensive backs, wide receivers and linebackers [26]. However the factor(s) responsible for higher core temperatures in linemen remains unclear. The primary focus of research has been on the potential role of hydration; and while marked dehydration can clearly exacerbate heat stress [10], the changes in hydration status typically shown in football players (-0.5% to -1.5%) do not correlate significantly with the magnitude of core temperature elevation [26].

Paragraph Number 3 Evaporative heat loss through sweating is the primary avenue of heat dissipation during exercise, particularly in hot environments where ambient air temperatures approach skin temperature [50]. The regional distribution of sweating has never been measured in football players. Moreover, Godek *et al.* [30, 62] are the only group to investigate positional differences in whole-body sweating. They showed that linemen (total body mass: 133±15 kg; BSA: 2.62±0.16 m^2) produced ~1 L/h more sweat than physically smaller backs (total body mass: 89±5 kg; BSA: 2.13±0.10 m^2)[30]. However these were on-field measurements during an actual NFL training camp, and as such, exercise intensity was likely greater in the heavier linemen in comparison to the lighter backs. Whole-body and local sweat rate in a fixed environment is directly influenced by the rate of evaporation required for heat balance (E_{req}) which in turn is primarily determined by the rate of metabolic heat production per unit surface area [58, 68-70]. It follows that regional sweating responses between linemen and backs cannot be independently compared unless both groups are exercising at the same rate of metabolic heat production per unit BSA under the same environmental conditions [73].

Paragraph Number 4 Given that the number of total sweat glands across the body is determined by the age of two [56], mass changes that occur beyond this point will not be coupled with a further increase in the total number of sweat glands. Therefore, in adults, the density of sweat glands decreases linearly with increasing BSA [28]. While the diameter and capacity of each sweat gland may be much larger in individuals with a greater BSA [66], a lower evaporative efficiency (i.e. the percentage of sweat produced that evaporates) may occur in larger players by virtue of a lower overall coverage of skin with sweat, resulting in a greater required sweat production to achieve a given amount of evaporation, and possibly greater increases in core temperature.

Paragraph Number 5 The aim of the present study was to investigate whether differences in regional upper body sweat rates between football linemen and backs exist independently of differences in metabolic heat production. It was hypothesized that at the same metabolic heat production per unit BSA, significantly greater sweating and core temperatures would still be observed in larger linemen relative to smaller backs indicating a lower evaporative efficiency in linemen.

METHODS

Participants

Paragraph Number 6 After approval of the experimental protocol by the University of Ottawa Research Ethics Board and University of South Florida (USF) Biomedical Institutional Review Board and after receiving informed consent, 12 National Collegiate Athletic Association (NCAA) Division I football players volunteered to participate in the study. For a comparison between the largest and the smallest players, six “linemen” (2 offensive guards, 2 offensive tackles and 2 defensive tackles) and six “backs” (2 wide receivers, 2 linebackers, 1 safety and 1 cornerback) were recruited based on position and body mass. Total body mass, height, and body fat percentage were taken prior to all experimental testing. Body fat percentage was determined using air displacement plethysmography (BodPod®, Life Measurements Inc., Concord, CA). Body surface area was estimated according to the equation provided by DuBois and DuBois (1916) [74] . Mean participant characteristics are presented in Table 1.

Instrumentation

Paragraph Number 7 Core Temperature (T_{core}): was measured using a telemetric pill sensor (HQ Inc. Palmetto, FL). Pills were ingested the night before testing just before going to bed at ~11pm for trials scheduled for earlier than 12pm the following day and at ~7am the same day for trials scheduled for later than 12pm. This allowed appropriate transit time for the pill to be located within the intestine when the participant arrived for testing [75-77]. Pills were administered to players by the USF athletic training staff in order to ensure the proper procedure was followed. Core temperature data was sampled every 15 s using a telemetric receiver (Data Recorder w/HR HT130042, HQ Inc, Plametto, FL) and was subsequently uploaded to a laptop computer (ThinkPad T60, Lenovo, North York, ON) at the end of the experimental trial.

Paragraph Number 8 Mean Skin Temperature (T_{sk}): Skin temperature was measured at 4 points (chest, shoulder, thigh, calf) using a wireless adhesive temperature sensor (iButton DS1922L, Embedded Data Systems, USA) secured to the skin surface using surgical tape (e.g. Blenderm, 3M, Canada). Each location was first shaved to remove any excess body hair and then wiped down with an alcohol swab before the placement of the iButton sensor. Mean skin temperature (T_{sk}) was estimated using the following weighted regional proportions: shoulder (30%), chest (30%), quadriceps (20%) and back calf (20%) [78]. The iButton system is a self-contained unit and therefore no real time data was displayed during the trial. Skin temperatures were sampled every 15 s and data was uploaded immediately after the trial. Although often used in the food industry and geological studies, iButtons have been recently validated for use in physiological applications [79, 80].

Paragraph Number 9 Local Sweat Rates (LSR): were measured using a modified version of the technical absorbent method previously reported by Havenith et al. [81] and Smith and Havenith [82]. Prior to each experimental trial, a set of absorbent material patches (#2164, Laminated Airlaid, Technical Absorbents Ltd, Grimsby, UK) were cut to size, individually placed in air-tight zip-lock freezer bags, marked and then weighed to the nearest 0.1 mg using a precision scale (Mettler Toledo AE240, Mississauga, ON, CA). A total of five distinct sweat zones were measured: Forehead (LSR_{head}) measured above the eyebrows and below the hairline at the mid-line of the nose; Forearm (LSR_{arm}) measured at the mid-point between the medial epicondyle of the humerus and the styloid process of the ulna on the supinated forearm; Chest (LSR_{chest}) measured 5 cm below clavicle at the center of left pectoral muscle; Shoulder ($LSR_{shoulder}$) measured 8 cm above the inferior angle of the left scapula on the infraspinous fossa; Lower back ($LSR_{lowback}$) measured 6 cm above the iliac crest and 5 cm to the left of the lumbar spinous processes. The surface area of all patches was 64 cm^2 (8.0 cm by 8.0 cm) with the exception of the forehead, which was 36 cm^2 (6.0 cm by 6.0 cm) in order to accommodate for the smaller sampling site. Surrounding each sweat patch was a 1 cm wide frame to prevent contamination of the sweat sample caused by the dripping of sweat from adjacent areas on the body.

Paragraph Number 10 For each sample period the contact site was first wiped with a dry towel to ensure that no moisture remained on the skin in the sampling area. The sweat patch (with frame) was then removed from the air-tight bag and placed on the appropriate site and subsequently held in place with a light compression garment. A headband (Skull Wrap, Product #8000072, Under Armour Inc, Baltimore, USA), forearm sleeve (Forearm Shiver, Product #8000033, Under Armour Inc, Baltimore, USA) and t-shirt (Compression Full Tee, Product #1000039, Under Armour Inc, Baltimore, USA) were used for the forehead, forearm and torso respectively and ensured an even distribution of pressure. After exactly 5-min the absorbent patch was removed from the surface of the skin, the frame was discarded and the patch placed in its own individualized zip-lock freezer bag. Following the conclusion of the trial each absorbent patch was weighed and local sweat rate for each site was calculated using the difference between pre- and post-application weight divided by the surface area of the patch (forehead: 36 cm^2, forearm:

64 cm^2) and the duration of application (5 minutes), giving values in milligrams per centimeter square per minute (mg•cm^{-2}•min^{-1}).

Paragraph Number 11 Metabolic data: was collected using a portable indirect calorimetry unit (Model K4b^2, COSMED, Chicago, IL) [83, 84] and displayed in real time on a laptop (ThinkPad T60, Lenovo, North York, ON). Subjects were equipped with a face mask that covered both the mouth and nose and were instructed to breathe normally. Metabolic measurements were collected continuously over the 60-min exercise protocol with the exception of the three local sweat rate sample periods at 10, 30 and 50-min of exercise.

Paragraph Number 12 Heart rate: Heart rate (HR) was monitored continuously throughout the trial using a Polar RS400X coded transmitter and stored to the aforementioned indirect calorimetry unit.

Protocol

Paragraph Number 13 Participants were transported in an air-conditioned vehicle to the laboratory situated at the School of Public Health at the University of South Florida, Tampa FL, in a well hydrated state, and having consumed a small meal. The number of linemen and backs being tested in the morning and afternoon sessions was balanced in order to ensure no order effect for time of day was present. When participants first arrived they were asked to change into the appropriate clothing (shorts, socks and running shoes (i.e. 0.1 clo)) and a researcher then verified the telemetric pill was present within their body by placing the telemetric receiver near the lower back. Once the pill was located participants were then instrumented with the 4 skin temperature sensors and body weight was recorded. Next, participants entered the thermal chamber (t_{db}: 32.4±1.0ºC; t_{wb}: 26.3±0.6ºC; v: 0.9±0.1 m/s) and were equipped with the portable indirect calorimetry system while sitting on an upright bike ergometer. Participants rested for 5-min in order to obtain baseline values for both metabolic and temperature data after which they began cycling for 60-min at a fixed cadence of 80 rpm at an external workload sufficient to elicit a fixed heat production of 350 W/m^2.

Paragraph Number 14 There were three separate sweat sampling periods during each trial. Each individual local sweat rate measurement lasted exactly 5-min. The measurements for the forehead and forearm commenced after 10, 30 and 50-min of exercise; while the measurements on the chest, upper and lower back commenced 90 s after those on the forearm and forehead, i.e. after 16.5, 31.5 and 51.5-min of exercise (Figure 1). The participant continued to cycle throughout each sweat sampling period. Following the completion of the torso sweat sample measurements the metabolic unit was placed back on the participant until the next sweat sample period.

Calculations

Paragraph Number 15 Metabolic energy expenditure (*M*): was obtained from minute-average values for oxygen consumption (VO_2) in Liters/min, and the respiratory exchange ratio (RER) using equation 1 [48]:

$$M = VO_2 \frac{\left(\frac{RER - 0.7}{0.3} e_c\right) + \left(\frac{1 - RER}{0.3} e_f\right)}{60 \times BSA} \times 1000 \text{ W/m}^2 \quad (1)$$

Where: e_c is the caloric equivalent per liter of oxygen for the oxidation of carbohydrates (21.13 kJ), and e_f is the caloric equivalent per liter of oxygen for the oxidation of fat (19.62 kJ).

Paragraph Number 16 External Work (W): was regulated and measured directly using an upright cycle ergometer (Ergomedic 828E, Monark Exercise, Langley, WA).

Paragraph Number 17 Sensible heat loss (C + R): The combined rate of convective (*C*) and radiative (*R*) heat exchange at the skin was calculated using equations 2 and 3 respectively [50] :

$$C = f_{cl} h_c \left(t_{cl} - t_{db}\right) \text{ W/m}^2 \qquad (2)$$

$$R = f_{cl} h_r \left(t_{cl} - t_{db}\right) \text{ W/m}^2 \qquad (3)$$

Where; f_{cl} is clothing area factor (since participants were very lightly clothed, this was assumed to be equal to BSA). t_{cl} is mean temperature of the clothed body in ºC (assumed to be equal to T_{sk}). Thermal resistance of clothing was assumed to be negligible since participants were semi-nude. h_c is the convective heat transfer coefficient in W/(m^2•K) and was estimated to be $8.3v^{0.6}$ [50]. h_r is the linear radiative heat transfer coefficient in W/(m^2•K). h_r was calculated using equation 4 [50]:

$$h_r = 4\varepsilon\sigma \frac{A_r}{BSA}\left[273.2 + \frac{\left(t_{cl} + t_r\right)}{2}\right]^3 \text{ W/(m}^2\text{•K)} \qquad (4)$$

Where; ε is the area weighted emissivity of the clothing body surface (assumed to be 1.0); is the Stefan-Boltzmann constant, 5.67 × 10^{-8} W/(m^2•K^4); A_r/BSA is the effective radiative area of body in m^2 (assumed to be 0.70 since the participants were seated); t_r is mean radiant temperature in ºC and was equal to t_{db}.

Paragraph Number 18 Respiratory heat loss by convection (C_{res}) and evaporation (E_{res}): was calculated using equation 5 [50]:

$C_{res} + E_{res} = [0.0014M\,(34 - t_{db}) + 0.0173M\,(5.87 - P_a)]$ ……………… W/m^2………………...(5)

Where: M is metabolic heat production in W/m^2; P_a is partial pressure of water vapour of ambient in kPa; t_{db} is dry bulb temperature in ºC.

Paragraph Number 19 Maximum evaporative capacity of the ambient environment (E_{max}): was calculated using equation 6 [50]:

$$E_{max} = \frac{w\left(P_{sk,s} - P_a\right)}{\left[\frac{1}{h_e}\right]}$$ ……………………………………………………W/m^2…..................(6)

Where: w is skin wettedness (during maximum evaporation skin is assumed to be completely wet therefore w is equal to 1.0); P_a the water vapour pressure in the ambient air in kPa; $P_{sk,s}$ is the partial water vapour pressure at the skin in kPa (assumed to be equal to saturated water vapour pressure at skin temperature); h_e is the evaporative heat transfer coefficient in W/(m^2•kPa^1) calculated using the Lewis Relation ($h_e = 16.5h_c$) [50]. Evaporative heat transfer resistance of clothing was considered to be negligible since the participants were semi-nude.

Paragraph Number 20 Evaporation required for heat balance (E_{req}): was calculated using equation 7:

$E_{req} = M - W - (C + R) - (C_{res} + E_{res})$ ……………………..……………W/m^2…………….(7)

Statistical Analyses

Paragraph Number 21 The data was first evaluated using a two-way ANOVA employing the fixed factors of positional group (2 levels: linemen (L) and backs (B)) and time (3 or 4 levels: rest, 10, 30, 50-min). Dependent variables were T_{core}, $\bar{T}_{sk}$, $\Delta\bar{T}_{sk}$, HR, LSR_{head}, LSR_{arm}, LSR_{chest}, $LSR_{shoulder}$, $LSR_{lowback}$, and the ratio of each local sweat rate relative to overall average upper body sweat rate. Any significant main effects or interactions between main effects were subjected to post-hoc analyses using independent t-tests. Furthermore, metabolic heat production was compared between linemen and backs using an independent t-test. The significance level was set at an alpha of 0.05 for all comparisons.

RESULTS

Heat Balance Parameters

Paragraph Number 22 Mean heat balance parameters for both linemen (L) and backs (B) throughout 60-min of exercise are given in Table 2. As intended, similar rates of metabolic heat production per unit surface area (M-W) were observed between L and B groups. Since sensible heat loss (C+R) and respiratory heat loss (C_{res}+E_{res}) were similar between L and B groups, so was the rate of evaporation required for heat balance (E_{req}). Moreover, the maximum theoretical rate of evaporation possible in the ambient environment (E_{max}) was not different between L and B groups, assuming both groups reached the same maximum skin wettedness. This resulted in a similar E_{req}:E_{max} ratio.

Local Sweat Rates (LSR)

Paragraph Number 23 Local sweat rate was significantly greater in the L group relative to the B group for measurements taken on the forearm, shoulder, chest and forehead (all $P<0.05$).

However, no significant differences were observed between L and B groups for local sweat rate measurement on the lower back (P=0.704). No significant interactions were found between time and player position for any of the local sweat rate measurements, therefore the differences in local sweat rate between L and B groups were sustained throughout exercise for arm, shoulder, chest and forehead measurements; and local sweat rate on the lower back remained similar between L and B groups throughout exercise. The local sweat rates measured in both L and B groups after 10, 30 and 50-min of exercise are illustrated in Figure 2.

Paragraph Number 24 The relative contribution of each local sweat rate site to the overall mean upper body sweat rate throughout exercise separated according to position group is illustrated in Figure 3. For both the L and B groups, the local sweat rate on the forehead was almost double the average upper body sweat rate, whereas the local sweat rate on the chest, forearm and shoulder was ~0.7 to 0.8 times that of the average upper body sweat rate. The relative contributions of forehead, forearm, shoulder and chest sweat rates to the average upper body sweat rate was the same in L and B groups, however the relative contribution of the lower back to average upper body sweat rate was significantly lower in the L group relative to the B group (P=0.006).

Core Temperature (T_{core})

Paragraph Number 25 No significant difference in core temperature was observed between L and B groups during pre-exercise rest, or during the initial 45-min of exercise. However a significant interaction between player position and time (P=0.012) was observed with core temperature significantly higher in the L group relative to the B group during the last 15-min of exercise (P=0.033). A comparison between the time dependent changes in core temperature throughout 60-min exercise of linemen and backs is illustrated in Figure 4a.

Mean Skin Temperature (T_{sk})

Paragraph Number 26 No significant main effect of position was found for absolute mean skin temperature; however analysis did reveal a significant interaction between time and player position ($P \leq 0.001$). While absolute mean skin temperature was not significantly different between L and B groups throughout 60-min exercise, the L group demonstrated much greater changes in mean skin temperature from pre-exercise rest relative to the B group after 10-min (L: 1.20±0.16ºC, B: 0.41±0.18ºC; $P<0.001$) 30-min (L: 1.58±0.22ºC, B: 0.74±0.17ºC; $P<0.001$) and 50-min (L: 1.52±0.24ºC, B: 0.77±0.26ºC; $P<0.001$) of exercise. A comparison between the time dependent changes in mean skin temperature throughout 60-min exercise of linemen and backs is illustrated in Figure 4b.

Heart rate (HR)

Paragraph Number 27 Mean HR responses throughout 60-min of exercise in both L and B groups are illustrated in Figure 4c. The HR responses were similar between L and B groups throughout the initial 30-min of exercise, however a significantly greater HR was observed in the L group relative to the B group after 45-min ($P=0.007$) and 60-min ($P=0.002$) of exercise.

DISCUSSION

Paragraph Number 28 The present study reveals, for the first time, that when metabolic heat production (M-W) per unit BSA and therefore the evaporation required for heat balance (E_{req}) per unit BSA is fixed between football linemen and backs during exercise in a hot environment (Table 2), linemen demonstrate significantly greater sweat rates on the forehead, chest, shoulder and forearm relative to backs. Furthermore, despite heat production per unit BSA being the same, and heat production per unit mass actually being ~25% lower in linemen (6.0±0.5 W/kg) in comparison to the backs (8.2±0.8 W/kg) by virtue of their significantly lower surface area-to-mass ratio, core temperature was in fact ~0.5˚C higher in linemen at the end of 60-min of exercise. Although previous research with both NFL and NCAA football programs have demonstrated greater whole-body sweating and larger elevations in core temperature in linemen [26, 30, 62, 85], the experimental conditions were such that previous studies could not identify whether different levels of heat stress were simply due to differences in metabolic heat production or also differences in the potential for heat dissipation. Our data suggests that football linemen have a compromised potential for heat dissipation independently of any difference in metabolic heat production.

Paragraph Number 29 Greater end-exercise elevations in core temperature suggest a greater heat storage per unit mass in linemen, therefore their lower heat production per unit mass must have been paralleled by a reduced heat dissipation despite significantly greater upper body sweating. As such, the proportion of sweat produced that evaporated (sweating efficiency) must have been much less in the linemen compared to the backs. Early research shows, that by the age of two, the total amount of sweat glands covering the human body has already been established [56]. Although there is inter-individual variation in the absolute number of sweat glands, it has been shown that as BSA and adipose tissue increase (typical in football linemen) distension of the skin reduces the number of sweat glands per unit of surface area effectively decreasing sweat gland density (SGD) in larger individuals [28]. With a lower SGD, the fraction of the total skin surface that could potentially be covered by secreted sweat (maximum skin wettedness) may be compromised since the spaces between neighboring sweat glands are larger. Sweat gland diameter and subsequently the capacity for sweat production per gland is greater in individuals with a greater BSA [66], and while this could compensate somewhat for a lower SGD in larger individuals in terms of sweat coverage over the skin, it likely elevates the proportion of secreted sweat that does not evaporate thus contributing further to a reduction in their sweating efficiency. In a given environment, a lower maximum skin wettedness in linemen would directly reduce their maximum theoretical rate of evaporation possible (E_{max} – equation 6) relative to backs, and subsequently increase their E_{req}:E_{max} ratio despite fixing environmental conditions and ensuring a similar E_{req} between positional groups (by prescribing the same metabolic heat production per unit BSA). Bain et al. [58] demonstrated that as the actual E_{req}:E_{max} ratio increases, local sweat rate measured on the forehead and forearm increases in parallel, presumably due to a reduction in sweating efficiency [57].

Paragraph Number 30 Linemen demonstrated a much greater body fat percentage (Table 1) and this could have partially contributed to the observed differences in end-exercise core temperature between position groups. The lower specific heat capacity of fat tissue would have yielded a lower average specific heat of the body in linemen (3.44 kJ/(kg•°C)) relative to backs (3.53 kJ/(kg•°C)), and therefore a given amount of heat stored in the body would have theoretically produced a slightly greater change in core temperature in linemen. However, while specific heat was <3% lower in linemen, heat production per unit mass was >25% lower, thus a greater heat storage per unit mass almost certainly occurred in the linemen group even when accounting for differences in body composition. It could be argued that a greater adipose tissue may have contributed to the apparent reduction in the potential for heat dissipation in linemen. However, while a greater subcutaneous fat layer may have played a role in the slightly lower resting skin temperatures [25] observed in linemen before the start of exercise, due to a lower thermal conductivity [86], it is likely that any insulative fat layers were by-passed by blood flow following the onset of exercise [15] – a notion supported by similar absolute skin temperatures between position groups during exercise.

Paragraph Number 31 Notwithstanding the apparently lower sweating efficiency in linemen, the potential differences in maximum skin wettedness between positional groups do not explain the physiological origin of the differences in sweating, particularly during the early stages of exercise. It is well established that the magnitude of elevation in skin temperature above baseline values promotes thermoregulatory sweating in the heat at equivalent core temperatures [87]. In the present study, linemen demonstrated significantly greater increases in mean skin temperature from baseline throughout exercise (Figure 4b) compared to backs. Since core temperatures were only statistically different between position groups during the final 15-min of exercise (Figure 4a), a greater activation in peripheral thermosensors may be the primary cause for the greater local sweat rates observed in linemen. When sweat rate at each location is expressed as a relative values compared to the average upper body sweat rate (i.e. mean of all 5 local sweat rate measurements) linemen do not seem to exhibit a disproportionately greater elevation in sweat rate in any one particular region (Figure 4). Furthermore, the distribution of relative sweat rates followed the same pattern in both position groups at 4 of 5 sites with the local sweat rate on the forehead being almost double (L: 184±26%, B: 174±24%) the average upper body sweat rate, with the arm, chest and shoulder all exhibiting values that were ~70 to 80% of the average upper body sweat rate. All relative values are not dissimilar from those previously reported in the literature [82] with the exception of the lower back showing lower absolute (L: 1.20±0.36 mg/(min•cm^2)) B: 1.26±0.48 mg/(min•cm^2)) and relative (L: 87±23% B: 57±12%) sweat rates in comparison to previous studies. This discrepancy is likely due to our measurement site being situated more towards the lateral aspect of the torso as opposed to directly over the lumbar spine in order to ensure complete contact between the technical absorbent patch and the skin surface.

Paragraph Number 32 Aerobic fitness was likely lower in linemen relative to backs as heart rate was the same between groups during the first 30-min of exercise and greater in linemen during the final 30-min of exercise (Figure 3c) despite oxygen consumption per unit mass being lower in linemen (L: 20.5±1.3 ml O_2/(kg•min); B: 28.3±2.6 ml O_2/(kg•min). A greater aerobic fitness no doubt facilitates a greater maximum sweat rate [67] however, greater sweating was observed in the position group that was probably less fit. Furthermore submaximal whole-body [68-70] and local [58] sweat rates have been clearly demonstrated to be primarily determined by the metabolic heat production (in W/m^2) irrespective of relative exercise intensity (i.e. percentage of VO_{2max}) and core temperature hence the design of the present experiment fixing the heat production per unit BSA between position groups.

Paragraph Number 33 While the approach adopted in the present study allows us to identify potential differences in the physiological capacity to dissipate heat, any observed on-field differences in heat stress between players are also likely due to differences in metabolic heat production. No research has thus far been conducted accurately measuring on-field energy expenditure and future research is needed to determine the relative contribution of metabolic heat production to the exacerbation of heat stress during live training camp activities. Sweat gland density (SGD) at each sweat sample site was not measured in the present study. Although a greater SGD was assumed in linemen by virtue of their greater BSA using evidence in the literature [28, 30, 55, 56, 66], a quantitative measurement of SGD and average sweat production per gland in both linemen and backs would support the proposed mechanism for the difference in sweating efficiency between groups. Future research studies should also include the evaluation of local sweat rates on the lower extremities in both linemen and backs in order to provide a greater insight into individual differences in heat dissipation potential. The possible influence of the technical absorbent material on both local skin temperature and skin saturation levels is unclear. An increase in skin saturation seems highly unlikely as the single highest observed sweat rate (1213 mg on the forehead in 5-min) equated to only 2.1% of the capacity of the absorbent patch (57175 mg for a 36 cm^2 patch). A greater local skin temperature at the sample site could have occurred which in turn could have influenced local sweat rate, however this potential effect was minimized due to short sample periods (5-min) and the use of small patch sizes. The fit of the compression t-shirt used to keep the absorbent patches in place and the subsequent pressure exerted on the sweat sample sites may have been slightly different between participants. However, it is unlikely that this fit effect is responsible for any differences observed in LSR between the linemen and backs since compression shirts of different sizes were selected depending upon the size of the participant, and greater local sweat rates were also observed on the forearm and forehead that were not covered by the compression t-shirt.

Paragraph Number 34 The present study has potentially important on-field practical applications as any intervention that would increase the evaporation of sweat without interfering with exercise intensity would be effective in mitigating heat stress risk, particularly in linemen. Due to the stationary nature of typical training camp drills for linemen, their lower self-generated wind velocity likely allows for less evaporative cooling for a given sweat production relative to their smaller counterparts [30]. However, our data suggest that even at similar air velocities (self-generated or otherwise) sweating efficiency would be lower in linemen. This position group should therefore be specifically targeted using the strategic placement of large mechanical fans during drills in order to potentially aid in the evaporation of sweat. Furthermore, since the lower sweating efficiency in linemen is attributed to a lower maximum skin wettedness, any artificial increase in skin wettedness with water misting stations (such as those currently used by some organizations) may compensate for this apparent morphologically-related disadvantage in linemen and reduce their heat stress risk. However, further investigation is required to assess the efficacy of these on-field interventions.

CONCLUSION

Paragraph Number 35 The present study demonstrated that football linemen sweat significantly more on the torso and head than football backs independently of any differences in metabolic heat production per unit BSA and therefore the rate of evaporation required for heat balance. Despite greater sweating and a lower heat production per unit body mass, linemen demonstrated significantly greater elevations in core temperature suggesting that sweating efficiency (i.e. the proportion of sweat that evaporates) was much lower in linemen.

ACKNOWLEDGEMENTS

This research was supported by a NFL Charities Medical Research Grant. The authors would like to thank the athletic training staff, players and coaching staff of the University of South Florida (USF) Football Program as well as Dr. Douglas Casa of the Korey Stringer Institute at the University of Connecticut. Special thanks also go to Prof. Tom Bernard of the School of Public Health at USF for generously granting us access to the climatic chamber and laboratory facilities, and Dr. Candi Ashley for her assistance throughout data collection. The results of the present study do not constitute endorsement by ACSM.

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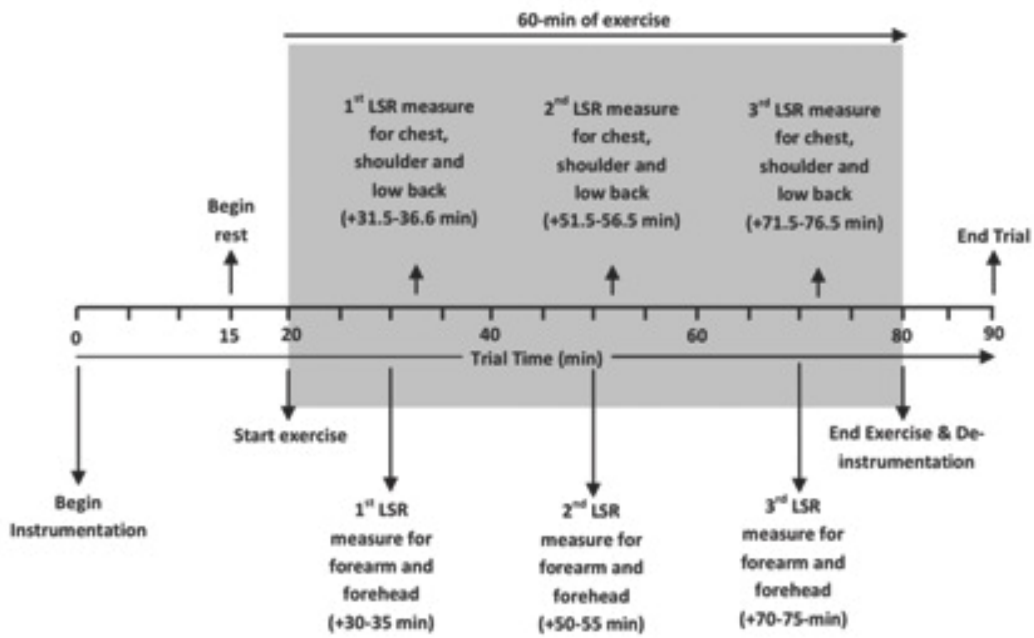
FIGURE CAPTIONS

Figure 1. Schematic drawing of test protocol. Five minute sweat samples on the forearm and forehead began after 10, 30 and 50-min. Samples on the chest, low back and shoulder began after 11.5, 31.5 and 51.5-min.

Figure 2. Average local sweat rates in linemen (*grey*) and backs (*white*) after 10-min, 30-min and 50-min exercise, and mean upper body sweat rate (*average of 5 sites*) for each time point at a fixed metabolic heat production of 350 W/m^2. Asterisk (*) indicates a significant difference between backs and linemen ($P \leq 0.05$). Error bars indicate standard error

Figure 3: The relative contribution of each local sweat rate site (LSR) to the overall mean upper body sweat rate (LSR_{mean} of 5 sites) across the entire 60-min exercise bout (LSR/LSR_{mean}) for linemen (*grey*) and backs (*white*). Asterisk (*) indicates a significant difference between backs and linemen ($P \leq 0.05$). Error bars indicate standard error.

Figure 4A-C. A comparison between linemen (*grey*) and backs (*white*) for, a) core temperature, b) mean skin temperature, and c) heart rate, throughout 60-min exercise at a fixed metabolic heat production of 350 W/m^2. Asterisk (*) indicates a significant difference between backs and linemen ($P \leq 0.05$). Error bars indicate standard error



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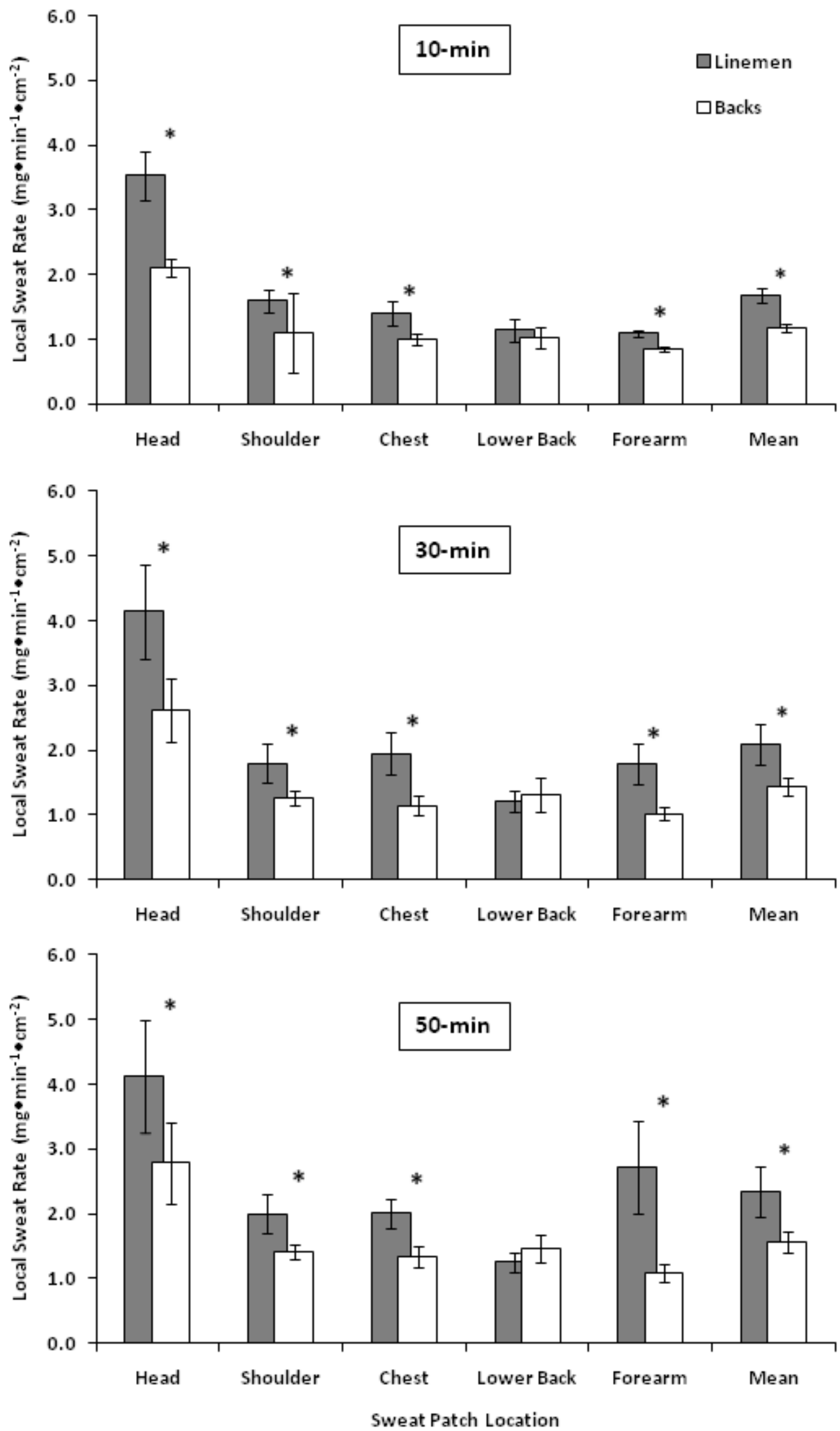

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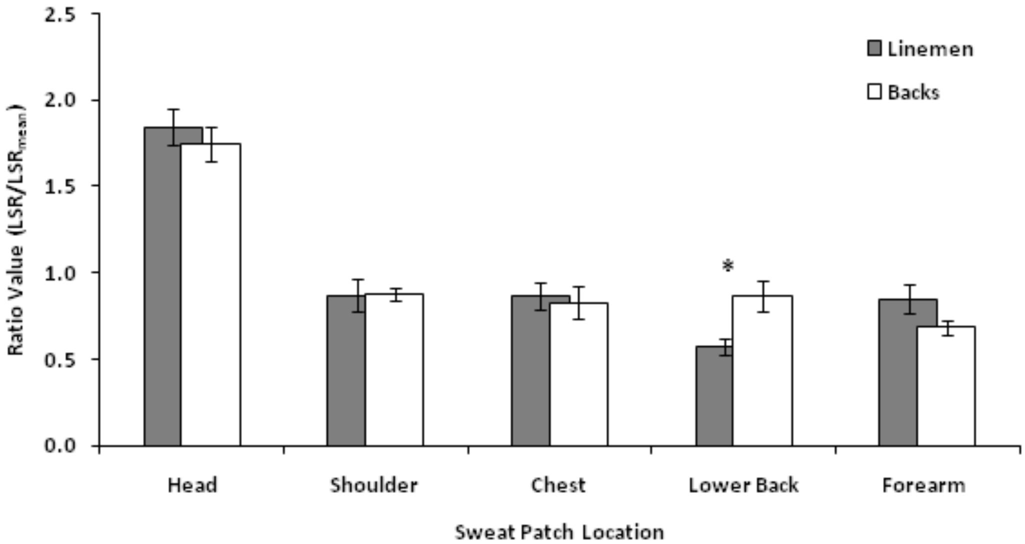

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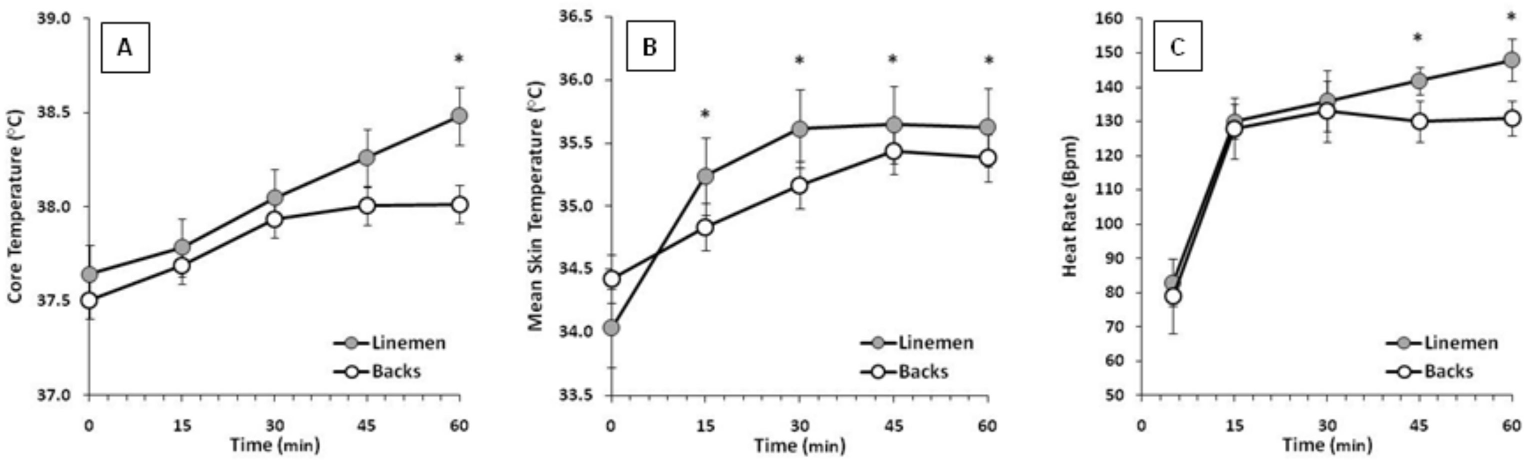

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STUDY #2: Heat balance status in NCAA football linemen and backs during summer training camp

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To be submitted to International Journal of Sports Medicine

This research was supported by a NFL Charities Medical Research Grant.

Running Title: "Heat balance parameters in NCAA football"

ABSTRACT. Purpose: To compare heat balance status between football linemen (L) and backs (B) during preseason summer training camp practices as a function of differences in self-generated convection. **Methods:** Fourteen NCAA Division 1 American football players [7 linemen (mass: 126±6 kg; BSA: 2.52±0.18 m^2) and 7 backs (mass: 88±13 kg; BSA: 2.09±0.18 m^2)] participated in on-field measurements over the first six days of summer training camp in southern Florida (T_{db}:31.2±1.6°C, T_{wb}:27.0±0.7°C, T_r:38.4±2.8°C). Simultaneous on-field measurements of self-generated air velocities (v_{self}) and mean skin temperatures (T_{sk}) were performed throughout practice, which included four drill categories (special teams, wind sprints, individual drills and team drills). Self-generated convective (h_c) and evaporative (h_e) heat transfer coefficients and resultant sensible heat losses (C+R) and maximum rate of evaporative heat loss (E_{max}) were calculated. Values were also combined to derive the maximum rate of metabolic heat production that is physiologically compensable (M_{max}). **Results:** Values for T_{sk} were similar between L and B for all drills ($p>0.05$). However, v_{self} and the resultant h_c and h_e values were greater in B at the upper two quartiles of running speeds for wind sprints and team drills, and at maximum running speeds for all four drills ($p<0.05$). Nonetheless, no differences in C+R or E_{max} were found between L and B for any drill category ($p>0.05$). However since L had a lower BSA-to-mass ratio (B: 240±17 cm^2/kg, L: 201±14 cm^2/kg) M_{max} per unit mass was lower in L for all drills ($p<0.05$). **Conclusion:** Greater running speeds in B elicit greater h_c and h_e, but despite similar T_{sk}, functionally different C+R or E_{max} values were not observed between positions. However a greater M_{max} per unit mass in B suggests a better capacity to maintain physiological compensability at higher work rates due to differences in body morphology.

INTRODUCTION

Paragraph Number 1 Exertional heat illnesses are a common concern among organizers of American football at all levels of competition [71, 88]. Participating athletes are at a particular risk during preseason summer training camps, with the combination of high ambient temperatures and humidity, high levels of exertion [7] and the thermal resistance of the equipment worn [7, 8] all contributing to marked elevations in core body temperature and an increased risk of heat exhaustion, heat syncope and heat stroke. Many athletic associations have implemented preventative measures and policies, such as the National Collegiate Athletic Association (Proposal 2002-84) mandatory heat acclimation protocol [10], in an effort to address heat-related health concerns. Nonetheless, heat illnesses remain commonplace in American football, with a total of 123 high school football players dying of heat-related illnesses between 1960 and 2009, and the death rate more than doubling in the past 15 years [11].

Paragraph Number 2 It has been well documented that the morphological variation between position groups among American football athletes is greater in comparison to other popular summer sports [30]. Compared to "backs" (i.e. defensive backs and wide receivers), "linemen" (i.e. offensive and defensive linemen) exhibit a much greater body mass, body surface area (BSA), higher percentage of body fat and a lower BSA-to-mass ratio [23, 24]. It is possible that these differences in physical characteristics increase the susceptibility of players of particular positions to exertional heat illnesses [14-16, 25]. Godek et al [26] reported significantly greater core temperature elevations in linemen during an NFL training camp compared to backs; and of the 58 high school football players dying of exertional heat stroke between 1980 and 2009, more than 85% were offensive or defensive linemen [11]. However, the underlying reasons for a greater heat strain and attendant risk of exertional heat illness in larger linemen remain unclear.

Paragraph Number 3 Deren et al. (2) recently reported a lower evaporative efficiency in linemen relative to backs during exercise at a fixed metabolic heat production per unit BSA in a climate controlled environment. Their data indicated a compromised capacity for heat dissipation via evaporation in linemen despite a greater sweat rate and similar skin temperatures, possibly due to a lower sweat gland density secondary to a greater BSA. However in a live training camp environment, Godek et al. [26] suggested that greater core temperature elevations in linemen during live football training camps may also arise in part from a lower self-generated air velocity (v_{self}), with a lower attendant convective and evaporative heat transfer, due to the more stationary nature of their position-specific activities. Combined with a smaller BSA-to-mass ratio, it is possible that the maximum metabolic heat production per unit mass (M_{max}) that can be physiologically compensated by linemen in the ambient environment is lower compared to backs which may in turn lead to the greater core temperature elevations typically observed in linemen.

Paragraph Number 4 The assessment of position-related heat balance parameters during summer football training camps has not been previously performed. Therefore, the aim of the present study was to conduct simultaneous measurements of on-field self-generated air velocities, mean skin temperatures and ambient conditions, and compare the estimated heat balance status between linemen and backs during summer football training camp practices. It was hypothesized that throughout a training camp practice significantly greater self-generated air velocities would be observed in backs compared to linemen. Consequently, a significantly greater heat transfer coefficient for convection (h_c) and evaporation (h_e) would be observed in backs despite similar mean skin temperatures. It was also hypothesized that after accounting for differences in body surface area-to-mass ratio, the maximum metabolic rate per unit mass that is physiologically compensable would be significantly lower in linemen relative to backs.

METHODS

Participants

Paragraph Number 5 Upon approval of the experimental protocol by the University of Ottawa Research Ethics Board, the University of Connecticut Institutional Review Board and the University of South Florida (USF) Biomedical Institutional Review Board and after receiving written informed consent, 14 National Collegiate Athletic Association (NCAA) Division I football players from the University of South Florida football program volunteered to participate in the study. In order to compare between the largest and the smallest players, seven "linemen" (4 defensive linemen, 3 offensive linemen) and seven "backs" (5 defensive backs, 1 tight end and 1 wide receiver) were recruited. Total body mass and height were taken prior to all experimental testing. Body surface area was estimated according to the equation of DuBois and DuBois [74]. Mean participant characteristics included; age (L: 20±1 y, B: 20±1 y), height (L: 190±5 cm, B: 182±8 cm), mass (L: 126±6 kg, B: 88±13 kg), body surface area (BSA) (L: 2.51±0.19 m^2, B: 2.09±0.18 m^2) and body surface area to mass ratio (BSA/mass) (L: 201±14 cm^2/kg, B: 240±17 cm^2/kg).

Instrumentation

Paragraph Number 6 Environmental Parameters: were measured on the sideline in an area free of obstructions that may have compromised the validity of the measurements (i.e. tree cover or fences). Measurements were taken during practice at 15-min intervals. Dry bulb (T_{db}) and wet bulb (T_{wb}) temperatures were measured using enclosed glass alcohol thermometers (ASTM thermometer 1003-3S, Thermco, Germany). Radiant temperature (T_r) was measured using a 150 mm diameter black globe and enclosed glass alcohol thermometer (ASTM thermometer 1003-3S, Thermco, Germany). Finally, ambient air velocity (v_{air}) was measured using a hot-wire anemometer (Hot Wire Anemometer HHF42, Omega, USA).

Paragraph Number 7 Mean Skin Temperature (T_{sk}): Skin temperature was measured at 4 points (chest, shoulder, thigh, calf) using a wireless adhesive temperature sensor (iButtonDS1922L, Embedded Data Systems, USA) secured to the skin surface using surgical tape (e.g. Blenderm, 3M, Canada). The measurement site was first shaved in order to remove any excess body hair and then wiped down with an alcohol swab before the placement of the iButton sensor. Mean skin temperature (T_{sk}) was estimated using the following weighted regional proportions: shoulder (30%), chest (30%), quadriceps (20%) and back calf (20%) [78]. The iButton system is a self-contained unit and therefore no real time data was displayed during the trial. Skin temperatures were sampled every 15 s and data were uploaded immediately after the trial. The iButton technology has been previously validated for use in physiological applications [79, 80].

Paragraph Number 8 Holter GPS data: On-field player speed ($m \bullet s^{-1}$) was measured using a wearable GPS system (MinimaxX 2.5; Catapult innovations, Melbourne, Australia) that has been previously assessed for both validity and reliability [89, 90]. The GPS unit was placed inside the pocket of a protective garment, and was then positioned at the upper back of the participant superior to the shoulder blades. The GPS unit and protective garment were worn underneath the player's team-issued protective equipment with no necessary modifications. GPS data were continuously recorded for the duration of each practice session. At the end of practice, participants returned the GPS device prior to leaving the field and the data were uploaded to a personal computer and stored for analysis using the manufacturer's software (LoganPlus 4.4.0, Catapult Innovations, Melbourne, Australia).

Protocol

Paragraph Number 9 Upon arrival at the training facility at the University of South Florida, Tampa, FL (Days 1-4) and Vero Beach, FL (Days 5-6), a maximum of 3 participants were recruited for testing each practice session. The number of linemen and backs tested each practice was balanced in order to ensure no order effect for time of day or equipment configuration was present (Table 2). Once selected and ~1 hour prior to the start of practice, participants were weighed and outfitted with the iButton skin temperature sensors and a Holter GPS system that had both been activated prior to their placement on the body. Once instrumented, participants were permitted to go about their daily routine while in the dressing room in preparation for practice. Researchers made contact with the participants once they reached the practice field to ensure the sensors remained in place and did not shift while the players were dressing. The practice was then allowed to proceed as scheduled with each player assigned their own researcher to monitor the status of the sensors and manually note the completed drills. The researchers were instructed to avoid interrupting the normal pace of the practice and were only to engage the player if needed while they were not participating in on-field drills. Practices consisted of 4 distinct drill categories, including "individual" and "team" drills as identified and categorized in previous research [26] as well as special teams and wind sprints. The order in which these drills occurred in practice was the same each day (i.e. special teams – wind sprints – individual drills – team drills). Upon completing practice, the iButton sensors and GPS system were retrieved prior to the player exiting the field.

Calculations

Paragraph Number 10 Self-generated convective heat transfer coefficient (h_{c_self}): At self-generated air speeds of >0.2 m/s, h_{c_self} was calculated using the following the equation. However, if v_{self} was <0.2 m/s, h_{c_self} was assumed to be 3.1 W/(m^2•K) [50].

$$h_{c\_self} = 8.3(v_{self})^{0.6} \ldots\ldots \text{W/(m}^2\text{•K)} \ldots\ldots (1)$$

Where v_{self} is the self-generated air velocity of each player in m•s^{-1} determined using the unit distance covered per unit time measured with the Holter portable GPS system.

Paragraph Number 11 Linear radiative heat transfer coefficient (h_r): was calculated using equation 2 [50]:

$$h_r = 4\varepsilon\sigma \frac{A_r}{BSA}\left[273.2 + \frac{(t_{cl} + t_r)}{2}\right]^3 \ldots\ldots \text{W/(m}^2\text{•K)} \ldots\ldots (2)$$

Where: ε is the area weighted emissivity of the clothing body surface (assumed to be 0.95); σ is the Stefan-Boltzmann constant, 5.67 × 10^{-8} W/(m^2•K^4); A_r/BSA is the effective radiative area of body in m^2 (assumed to be 0.73 since the participants were primarily in the upright position) [50]; t_{cl} is the mean temperature of the clothed body in ºC (calculated using the iteration method) [50] and t_r is mean radiant temperature in ºC, measured using a 150 mm diameter black globe thermometer.

Paragraph Number 12 Combined heat transfer coefficient ($h_{\_self}$): Calculated by adding both convective and linear radiative heat transfer coefficients [50]:

$$h_{\_self} = h_{c\_self} + h_r \ldots\ldots \text{W/(m}^2\text{•K)} \ldots\ldots (3)$$

Where h_{c_self} is the calculated convective heat transfer coefficient (equation 1) and h_r is the calculated linear radiative heat transfer coefficient (equation 2).

Paragraph Number 13 Sensible heat loss (C + R): The rate of combined convective (C) and radiative (R) heat loss at the skin was calculated using equation 4 [50].

$$C + R = \frac{(t_{sk} - t_o)}{\left(R_{cl} + \frac{1}{f_{cl} h\_self}\right)} \text{ W/m}^2 \quad (4)$$

Where: t_{sk} is mean skin temperature measured using iButton sensors. t_o is the operative temperature calculated using the equation below (equation 5). f_{cl} is the clothing area factor while R_{cl} is the thermal resistance of clothing which were variable from practice to practice and dictated by the mandatory NCAA heat acclimation protocol [10]. Values for f_{cl} and R_{cl} have been previously determined using thermal manikins for the three equipment configurations used in the present study (shorts, shells and full) [47]. As such, f_{cl} values were (shorts: 1.1085, shells: 1.1953, full: 1.3038) while R_{cl} were (shorts: 0.05425 m^2•K/W, shells: 0.09765 m^2•K/W, full: 0.1519 m^2•K/W. $h_{\_self}$ is the combined heat transfer coefficient calculated using equation 3 [50].

$$t_o = \frac{(h_r t_r + h_{c\_self} t_{db})}{h_r + h_{c\_self}} \text{ °C} \quad (5)$$

h_r is the linear radiative heat transfer coefficient in W/(m^2•K), calculated using equation 2 [50]: t_r is mean radiant temperature in ºC, h_{c_self} is the convective heat transfer coefficient calculated using equation 1. t_{db} represents mean dry bulb temperature.

Paragraph Number 14 Respiratory heat losses by convection (C_{res}) and evaporation (E_{res}): were calculated using equation 6 [50]:

$$C_{res} + E_{res} = [0.0014M(34 - t_{db}) + 0.0173M(5.87 - P_a)] \ldots \text{W/m}^2 \ldots\ldots\ldots\ldots (6)$$

Where: M is the mean estimated metabolic heat production (370 W/m^2) for both linemen and backs, calculated using Equation 7 below; P_a is the partial pressure of water vapour of ambient air in kPa; t_{db} is dry bulb temperature in ºC [48].

$$M = VO_2 \frac{\left(\frac{RER-0.7}{0.3}e_c\right)+\left(\frac{1-RER}{0.3}\right)}{60 \times BSA} \times 1000 \ldots\ldots\ldots\ldots \text{W/m}^2 \ldots\ldots\ldots\ldots (7)$$

Where VO_2 was obtained using average metabolic data (VO_{2max}) (4.5 L/min) previously obtained from a range of player positions [65] assuming on field metabolic energy expenditure to be approximately 55% of VO_{2max} [7], and an assumed respiratory quotient (RQ) of 0.85 [50]; e_c and e_f are the caloric equivalents per liter of oxygen for the oxidation of carbohydrates (21.13 kJ) and fats (19.62 kJ).

Paragraph Number 15 Self-generated evaporative heat transfer coefficient (h_{e_self}): was calculated using the Lewis Relation [50]:

$$h_{e\_self} = 16.5 h_{c\_self} \ldots\ldots\ldots\ldots \text{W/(m}^2\text{•kPa)} \ldots\ldots\ldots\ldots (8)$$

Where h_{c_self} is the calculated convective heat transfer coefficient (equation 1).

Paragraph Number 16 Maximum evaporative capacity of the ambient environment (E_{max})*:* was calculated using equation 9 [50]:

$$E_{max} = \frac{w\,(P_{sk,s} - P_a)}{\left[R_{e,cl} + \frac{1}{f_{cl} \cdot h_{e\_self}}\right]} \text{………………………………………… W/m}^2\text{……..........…...(9)}$$

Where: *w* is skin wettedness. During maximum sweating, skin is assumed to be completely wet; therefore *w* is equal to 1.00. Based on recent findings [91] *w* was also adjusted to 0.85 for linemen [92] to calculate $E_{max,adj}$; P_a is the water vapor pressure in the ambient air in kPa; $P_{sk,s}$ is the partial water vapor pressure at the skin in kPa (assumed to be fully saturated at a given skin temperature); $R_{e,cl}$ is the evaporative heat transfer resistance of the clothing layer as measured previously (22) (shorts: 0.009 m^2•kPa/W, shells: 0.017 m^2•kPa/W, full: 0.022 m^2•kPa/W); f_{cl} is the clothing area factor as measured previously (22) (shorts: 1.1085, shells: 1.1953, full: 1.3038); h_{e_self} is the evaporative heat transfer coefficient in W/(m^2•kPa) (Equation 8) [50].

Paragraph Number 17 Maximum metabolic rate that is physiologically compensable (M_{max}): was calculated using equation 9 [50]:

$$M_{max} = \frac{(C+R)+(C_{res}+E_{res})+E_{max}}{b_m} \text{ …………………….……...W/kg…………………...(10)}$$

M_{max} was calculated using the maximum (4th quartile of $v_{\_self}$) values of C+R and E_{max}; b_m is total body mass (kg). Furthermore, based on recent findings [91], $M_{max,adj}$ is calculated for the linemen by substituting E_{max} for $E_{max,adj}$ calculated for the 4th quartile of $v_{\_self}$ (equation 9).

Statistical Analyses

Paragraph Number 18 All data are presented as the mean ± standard deviation. Mean overall ambient conditions (t_{db}, t_{wb}, t_r and v_{air}) were compared between linemen (L) and backs (B) using two-tailed independent samples t-tests. T_{sk} was compared between L and B for each of the four drill categories using two-tailed independent samples t-tests. Data for v_{self} were expressed as quartiles and the overall mean for each of the 4 drill categories, and compared between L and B using one-tailed independent samples t-tests. Furthermore, $h_{c\_self,}$ h_{e_self}, C+R and E_{max} values for both L and B were compared using one-tailed independent samples t-tests for the mean and each quartile speed for each drill category. Finally, M_{max} was compared between L and B at the maximum self-generated air speed (4^{th} quartile) for each drill category using a one-tailed independent samples t-test. The significance level was set at an alpha of 0.05 for all comparisons.

RESULTS

Ambient Conditions

Paragraph Number 19 Mean ambient conditions, along with equipment configurations and practice start times are shown in Table 1. As intended, no significant differences were seen between L and B for mean T_{db} (p=0.43), mean wet bulb temperature (T_{wb}) (p=0.64), mean T_r (p=0.52) and mean ambient air velocity (v_{air}) (p=1.00) over the 6-day testing period.

Mean Skin Temperature (T_{sk})

Paragraph Number 20 Average mean skin temperature (T_{sk}) was not significantly different between L and B groups throughout practice (p=0.92). Furthermore, there were no significant differences in T_{sk} between L and B for each individual drill category:"special teams" (p=0.48), "wind sprints" (p=0.94), "individual drills" (p=0.97) and "team drills" (p=0.86). A comparison of T_{sk} between L and B for the overall practice and each drill category is illustrated in Figure 1.

Self-generated Air Velocity (v_{self})

Paragraph Number 21 Comparisons of v_{self} between L and B throughout training camp practice organized by quartiles and overall average are illustrated in Figure 2. After separating the v_{self} data according to drill category, no significant differences were observed at the 1st and 2nd quartiles between L and B in each of the four drill categories. However, v_{self} at the 3rd quartile was significantly greater in B during "wind sprints" (p=0.018) and while maximal v_{self} (4th quartile) was significantly higher in B compared to L during all drills; "special teams" (p=0.002), "wind sprints" (p=0.014), "individual drills" (p=0.002) and "team drills" (p=0.004). Finally, mean v_{self} was greater in B compared to L for "wind sprints" (p=0.024) and "team drills" (p=0.012).

Convective and evaporative heat transfer coefficients

Paragraph Number 22 Differences in both self-generated convective (h_{c_self}) and evaporative (h_{e_self}) heat transfer coefficients between L and B calculated using five measured v_{self} values (mean, and 1st, 2nd, 3rd and 4th quartile) for each of the four drill categories are illustrated in Figure 3. Since h_e is directly related to h_c by virtue of the Lewis relation (equation 8), p-values for both h_c and h_e are equivalent. Backs demonstrated significantly greater h_{c_self} and h_{e_self} values compared to L at the 3rd quartile of v_{self} during "wind sprints" (p=0.016). Furthermore, B had significantly greater h_{c_self} and h_{e_self} values compared to L at maximal v_{self} (4th quartile) for all four drill categories; "special teams" (p=0.002), "wind sprints" (p=0.016), "individual drills" (p=0.002) and "team drills" (p=0.004). Finally, both h_{c_self} and h_{e_self} were significantly greater in B at mean v_{self} for "wind sprints" (p=0.028) and "team drills" (p=0.042) when compared to L.

Heat balance parameters

Paragraph Number 23 Mean heat balance parameters in both linemen (L) and backs (B) for each of the four drill categories separated by self-generated air velocities (v_{self}) are listed in Table 2. Sensible heat loss (C+R) was not different between L and B for any of the drills tested ($p>0.05$). Assuming no differences in maximum skin wettedness between groups (w=1.00), no significant differences were found for E_{max} (per unit BSA) between L and B for each of the four drills at any level of v_{self} (quartiles or mean) ($p>0.05$). However, when $E_{max,adj}$ (per unit BSA) was calculated with an adjusted w in L (w=0.85), B demonstrated greater $E_{max,adj}$ values for "wind sprints" (p=0.003) at the 3^{rd} quartile of v_{self}.

Maximum compensable metabolic heat production (M_{max})

Paragraph Number 24 When assuming a skin wettedness (w) of 1.00 in both L and B, backs demonstrated significantly greater values for M_{max}(W/kg) at maximal v_{self} for all drills of "wind sprints" (p=0.028) and "team drills" (p=0.009) (Figure 4). Furthermore, when skin wettedness was adjusted in the L (w= 0.85), this difference was exacerbated with B showing a significantly greater $M_{max,adj}$ (W/kg) at maximal v_{self} while participating in all drills: "wind sprints" (p=0.002), "special teams" (p=0.004), "individual drills" (p=0.002), and "team drills" (p=0.002) (Figure 4).

DISCUSSION

Paragraph Number 25 The present study demonstrates that during a typical summer training camp football practice, backs exhibit significantly greater self-generated air velocities (Figure 2) and therefore significantly greater heat transfer coefficients for both convection (h_c) and evaporation (h_e) (Figure 3) relative to linemen. When combined with similar on-field mean skin temperatures measured between linemen and backs, differences in the heat transfer coefficients did not lead to differences in sensible heat loss (C+R) or the maximum capacity for evaporation per unit body surface area (E_{max}) during on-field drills (Table 2). However, when calculating the maximum rate of metabolic heat production per unit mass that could be physiologically compensable through both dry and latent heat losses (M_{max}), linemen demonstrated values that were ~20% lower then the backs. Furthermore, after accounting for the significantly smaller BSA-to-mass ratio and the reduced maximum skin wettedness previously suggested in linemen (2), the difference in M_{max} was further exacerbated with linemen showing values ~30% lower for all drill categories compared to backs.

Paragraph Number 26 Evaporative heat loss through sweating is the primary avenue for heat dissipation during exercise, particularly in hot environments where ambient air temperatures approach skin temperature [50]. However, in environments of high ambient humidity and radiant heat load such as those observed in the present study (Table 1) and those typically occurring at summer football training camps [62, 72], the ability to dissipate heat through evaporation would be diminished as the gradient between P_{sk} and P_a becomes progressively smaller. As such, with no differences in mean skin temperature (Figure 1) or ambient air temperatures (Table 1) between L and B, any potential differences in convective heat loss and consequently the maximal evaporative capacity (E_{max}) would be determined by differences in self-generated air velocities (v_{self}) by virtue of its influence on both the convective and evaporative heat transfer coefficients.

Paragraph Number 27 The greater observed v_{self} in B compared to L during each of the four drill categories (Figure 2) confirms previously suggested positional differences in on-field player movement [26]. However, these significant differences in v_{self} did not occur throughout an entire practice session; rather, backs demonstrated greater values for v_{self} only at the 3rd quartile, 4th quartile and average v_{self} values (Figure 2) with no significant differences observed for the 1st or 2nd quartiles in any drill category. These data are consistent with the intermittent nature of the sport [93], but also show that backs reach significantly greater average and maximal speeds throughout a typical practice, while both linemen and backs spend >50% of their time at equivalent (low) speeds indicative of rest intervals, substitutions, water breaks, demonstrations or walk through drill components. This is in agreement with previously suggested differences in positional demands for on-field player movement between linemen and backs [26]. Lineman-specific positional requirements tend to be more static in nature, requiring short steps when blocking opposing players often with minimal amounts of actual distance covered. Alternatively, the positional requirements for backs are typically sprint-based and require the player to cover large amounts of the field in the shortest time possible in an attempt to out-run or keep up with the opposing player, thereby generating large air velocities.

Paragraph Number 28 The significantly greater self-generated air velocities in backs translated into significantly greater h_{c_self} and h_{e_self} compared to linemen (Figure 3). However, when combined with the similar T_{sk} (Figure 1) and ambient conditions (Table 2) between L and B in all drills, the estimated sensible heat loss and E_{max} were similar between linemen and backs (Table 2). This somewhat counterintuitive observation is described by the nonlinear relationships between h_{c_self} and sensible heat loss (Equation 4), and h_{e_self} and E_{max} (Equation 9). As such, large changes in h_{c_self} above values of ~10 W/(m^2•K) yield relatively small absolute changes in sensible heat loss. Likewise, large changes in h_{e_self} above values of ~150W/(m^2•kPa) will yield relatively small absolute changes in E_{max}. It follows that if substantial differences between L and B for h_{c_self} and h_{e_self} occurred at lower self-generated air speeds (e.g. 1st and 2nd quartiles), it is likely that meaningful differences in sensible heat loss and E_{max} would have been observed; however, this was not the case in the present study. As training camp practices took place in the early afternoon, high levels of on-field solar radiation (T_r) were unavoidable, as such T_r often exceeded T_{sk} resulting in a temperature gradient that promoted a net radiative heat gain from the environment to the body. On the other hand, T_{sk} remained higher then T_{db} and unlike radiative heat exchange, this temperature gradient promoted a net heat loss to the environment via convection. Therefore, competing sensible heat exchange avenues resulted in very low net sensible heat loss in both linemen and backs (Table 2), thereby demanding an increased reliance on evaporative heat loss to achieve heat balance.

Paragraph Number 29 Although no significant differences were shown in sensible heat loss (C+R) and E_{max} between linemen and backs, recent work by Deren et al. [91] suggests that compared to backs, linemen may in fact have a diminished maximum evaporative heat loss response due to a lower skin wettedness secondary to a lower sweat gland density. When calculating E_{max} in the present study it was first assumed that the maximal skin wettedness possible in an individual is equivalent to 1.00 [50, 94]. Although more research is needed to quantify the reduced maximum skin wettedness in linemen, for the purpose of this analysis, a value of 0.85 was employed to provide an additional adjusted $E_{max,adj}$ value in linemen, since this value has similarly been used to account for an impaired maximum skin wettedness in previous studies [50]. Nonetheless, at an equivalent maximal skin wettedness (*w*=1.00), linemen still demonstrated a ~20% lower M_{max} (W/kg) in all four drill categories (Figure 4) almost exclusively due to the lower BSA-to-mass ratio in linemen relative to backs. This difference in M_{max} between position groups was then exacerbated further (~30%) when maximum skin wettedness was reduced to 0.85 in linemen (Figure 4). Although these data indicate that backs can perform greater work rates before reaching physiological uncompensability during summer training camps, an actual measurement of on-field metabolic energy expenditure still merits further investigation in order to truly understand the mechanisms behind the susceptibility of linemen to greater increases in core temperature.

Limitations

Paragraph Number 30 While the approach adopted in the present study allowed for the measurement of on-field v_{self} and T_{sk} in7 linemen and 7 backs, v_{self} was only assessed by means of whole-body displacement, and as such any additional differences in self-generated air velocity provided by differences in arm swing or leg drive could not be accounted for. Although these differences likely exist, the nature of training camp drills (v_{self}> 1.0 m/s) placed both positional groups at the higher end of the nonlinear relationships between h_{c_self} and sensible heat loss (Equation 4), and h_{e_self} and E_{max} (Equation 9) and therefore any additional increase in v_{self} would likely have not resulted in meaningful differences in total heat loss potential. Additionally, although self-generated and ambient air velocities were measured, the direction of air flow could not be accounted for as training camp drills demanded multidirectional movement from both position groups. No direct measure of core temperature was available in the present study, however linemen have consistently shown greater core temperature increases during on-field training camp practices when compared to backs [26, 91]. Finally, metabolic heat production (M) was considered equivalent between linemen and backs since no direct measure of M was available when calculating respiratory heat losses. This was based on previously reported VO_2 results [65] for a variety of positions and estimated energy expenditure [7] from a simulated practice in the heat. Although on-field metabolic heat production was likely different and merits further investigation, similar ambient conditions and the probable similarities in lung capacity, and therefore equivalent tidal volumes between linemen and backs suggest minimal differences in C_{res} and E_{res}. Future studies should focus on collecting actual on-field metabolic data for a variety of position-specific drills in order to access the compensability of these drills for each position by comparing the actual on-field metabolic data to M_{max} calculations.

Practical Applications

Paragraph Number 31 The present study has potentially important on-field practical applications as it suggests that the largest limitation for heat loss amongst American football linemen is a lower BSA-to-mass ratio when compared to backs. As such, future safety guidelines should take into consideration morphological variability when identifying players potentially at an increased risk for developing heat illness. Additionally, safety guidelines developed for adults should be revised when applied to youth football as children exhibit even larger variations in body morphologies from one year to the next. Furthermore, the results of the present study demonstrate for the first time, that while differences in v_{self}, h_c and h_e exist between linemen and backs, these differences do not significantly alter heat balance parameters between the groups. As such, any intervention aimed at increasing convection by eliciting a greater air velocity while players are participating in on field drills (i.e. mechanical fans) will have a minimal influence on both convective and evaporative heat loss. However, these same interventions may be crucial during rest intervals or water breaks when players are standing still ($v_{self} \sim 0$).

Paragraph Number 32 With no differences in heat balance parameters observed due to differences self-generated air velocity in the present study, the primary focus of training staff and coaches should potentially shift to reducing metabolic heat production, particularly in larger players. While high rates of metabolic heat production are inevitable, adequate recovery time between drills with supplemental cooling interventions will likely reduce the occurrence of unsafe levels of heat strain.

CONCLUSIONS

Paragraph Number 33 The present study demonstrated that relative to linemen, backs exhibit significantly greater self-generated air velocities (v_{self}) and therefore significantly greater heat transfer coefficients for both convection (h_c) and evaporation (h_e) over the course of summer training camp practice. However, the significantly greater v_{self} in backs, when combined with a lack of difference in on-field T_{sk} between position groups, did not lead to differences in sensible heat loss (C+R) or E_{max} between position groups. However most importantly, the larger BSA-to-mass ratio in backs resulted in a higher maximum compensable metabolic heat production (M_{max}) per unit mass, a difference which was exacerbated when the maximum skin wettedness in linemen was reduced from 1.00 to 0.85. The actual on-field metabolic requirements of linemen-specific drills when combined with the observed lower M_{max} compared to backs may predispose these athletes to greater heat injury risk; however, this merits future investigation.

ACKNOWLEDGEMENTS

This research was supported by a NFL Charities Medical Research Grant. The authors would like to thank the athletic training staff, players and coaching staff of the University of South Florida (USF) Football Program. Special thanks also go to Prof. Tom Bernard of the School of Public Health at USF for his generous advice and assistance. The results of the present study do not constitute endorsement by ACSM.

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Table 1. Daily ambient conditions, equipment configurations and practice start times over six days of summer training camp

Characteristics	Day 1 (n=2)	Day 2 (n=1)	Day 3 (n=3)	Day 4 (n=3)	Day 5 (n=3)	Day 6 (n=2)
Dry Bulb (T_{db}), °C	32.4±1.8	34.2±1.4	29.7±1.9	32.2±0.5	31.5±0.9	28.7±1.7
Wet Bulb (T_{wb}), °C	27.4±0.7	27.5±0.7	27.5±0.9	27.6±0.4	26.3±0.4	25.9±0.7
Black Globe (T_r), °C	40.5±5.4	44.1±4.4	35.8±3.8	38.7±1.8	40.0±1.7	34.6±4.9
Avg. Air Velocity (v_{air}), $m\bullet s^{-1}$	1.3±0.7	1.1±0.6	0.6±0.7	2.6±0.5	3.1±1.0	1.7±0.6
Equipment Configuration	Shorts	Shorts	Shells	Shells	Full	Shells
Practice Start Time	15:40	15:40	15:40	13:40	15:40	8:30
Positions Represented (L=linemen, B=backs)	1L, 1B	1L	1L, 2B	2L, 1B	1L, 2B	1L, 1B

Values given are means (± SD) Equipment configurations included: "shorts" (shorts, mesh jersey and helmet), "shells" (shorts, shoulder pads, mesh jersey and helmet) and "full" (pants, girdle, mesh jersey, shoulder pads, thigh pads and helmet)

Table 2. Mean heat balance parameters in linemen and backs for each of the four specific drill categories calculated at all four quartiles of v_{self} and average v_{self} for each drill.

		C+R, (W•m^{-2})		E_{max}(W•m^{-2})	
V_{self}	Drill Category	Linemen	Backs	Linemen	Backs
1st Quartile	Special Teams	-1±14	3±11	83±22	77±10
	Wind Sprints	2±14	9±7	82±18	80±7
	Individual Drills	0±17	5±10	82±15	81±12
	Team Drills	-5±14	3±11	63±18	73±16
2nd Quartile	Special Teams	-1±14	3±11	83±22	77±10
(Median)	Wind Sprints	2±14	9±7	82±18	80±7
	Individual Drills	0±17	5±10	82±15	81±12
	Team Drills	-5±14	3±11	63±18	73±16
3rd Quartile	Special Teams	2±15	7±13	93±20	88±16
	Wind Sprints	6±17	18±9	93±15	101±6
	Individual Drills	0±16	6±8	85±15	90±28
	Team Drills	-5±14	6±10	63±18	84±25
4th Quartile	Special Teams	18±15	26±14	141±53	128±38
(Max)	Wind Sprints	25±15	34±12	139±54	123±7
	Individual Drills	20±15	30±12	140±47	134±41
	Team Drills	14±17	29±15	105±48	130±40
Average	Special Teams	1±14	6±12	90±22	85±15
	Wind Sprints	6±16	14±8	94±16	94±11
	Individual Drills	-1±15	7±9	83±14	90±23
	Team Drills	-5±14	6±11	63±17	81±19

Values given are means (± SD). C_{res}+E_{res} values were equivalent for all drills between groups (18 W•m^{-2}).

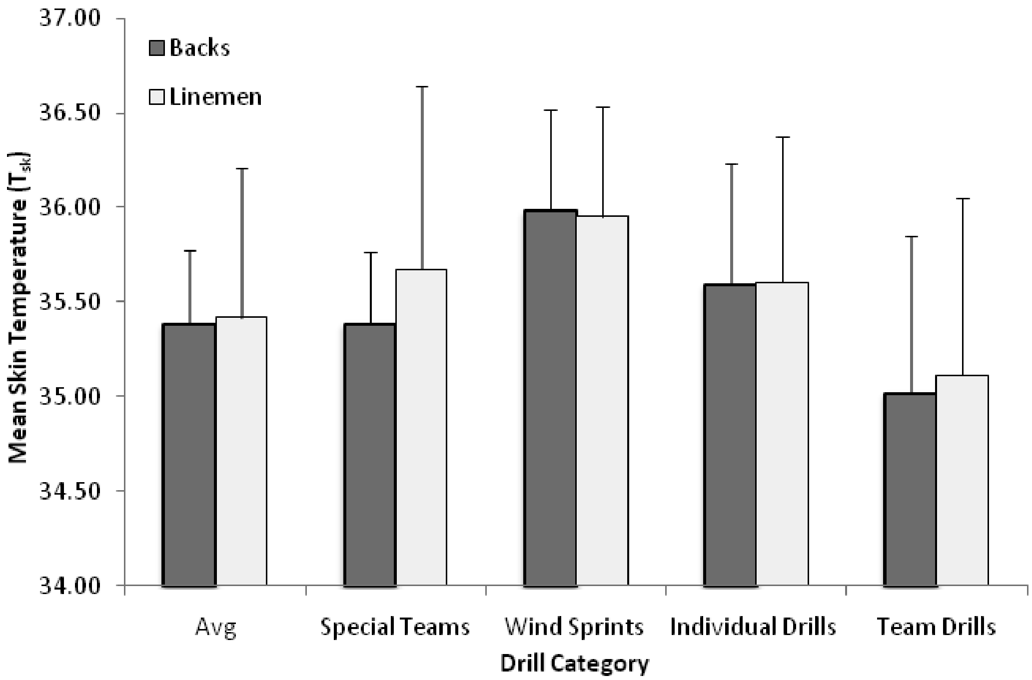

Figure 1: A comparison of mean skin temperature (T_{sk}) between backs (grey) and linemen (white) over the entire practice (avg) and during four key drill classifications. Error bars indicate standard deviation

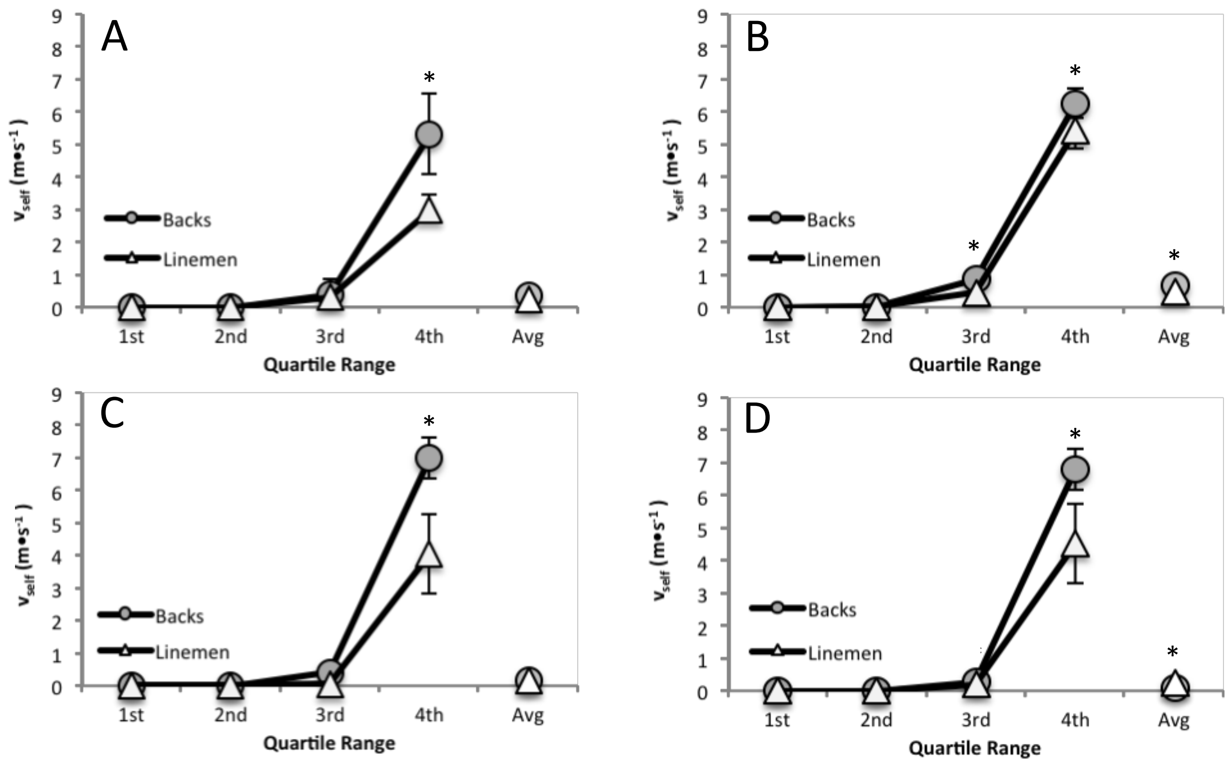

Figure 2: A comparison of self-generated air velocities (v_{self}) between backs (grey circles) and linemen (white triangles) during typical training camp drills including: A) special teams B) wind sprints C) individual drills and d) team drills. v_{self} values were compared at each quartile and overall mean for each drill category. Asterisk (*) indicates a significant difference between backs and linemen ($P \leq 0.05$). Error bars indicate standard deviation.

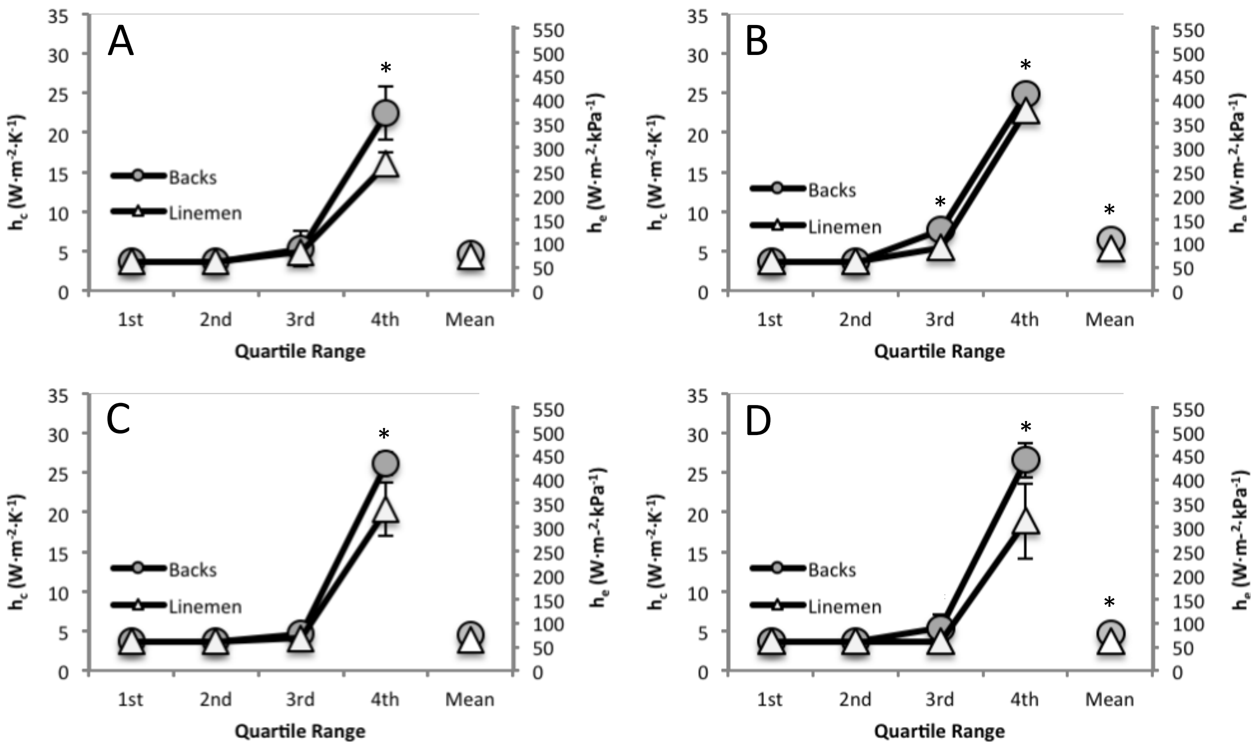

Figure 3: A comparison of both self generated and total convective (h_c) and evaporative (h_e) heat transfer coefficients between backs (grey circles) and linemen (white triangles) during typical training camp drills including: A) special teams B) wind sprints C) individual drills and D) team drills. Asterisk (*) indicates a significant difference between backs and linemen (P≤0.05). Error bars indicate standard deviation.

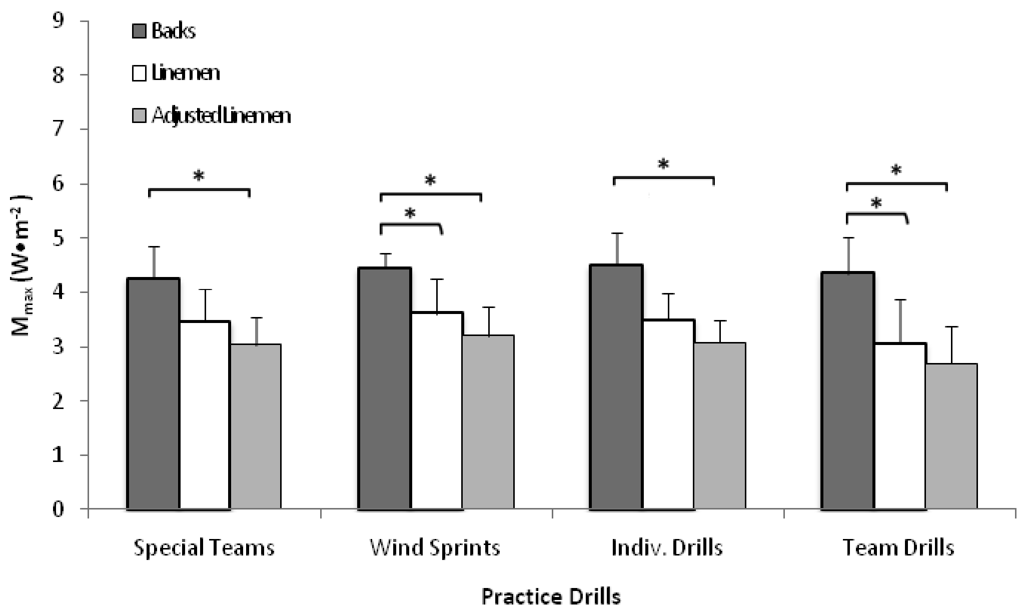

Figure 4 :A comparison of the maximal theoretical compensable metabolic heat production (M_{max}) between backs (dark grey) and linemen (white) during four key drill classifications. A third column (light grey) represents an adjusted M_{max} (M_{max_adj}) based on suggestions by Deren et al. [91] that take into account a lower maximal skin wettedness in linemen (*w*=0.85) and therefore a lower adjusted E_{max} (E_{max_adj}). Asterisk (*) indicates a significant difference between backs and linemen ($p \leq 0.05$). Error bars indicate standard deviation.

PART THREE: DISCUSSION AND CONCLUSION OF THE THESIS

3.1 Discussion

To date, the primary causes for the higher core temperatures observed in American football linemen relative to backs [26] during summer training camp conditions remain unknown. As such, the purpose of this thesis was to examine the differences in thermoregulatory responses between specific position groups using a novel heat balance approach. The two studies detailed in this thesis aimed to elucidate: 1) whether differences in regional upper body sweat rates (on the forehead, forearm, shoulder, chest and lower back) exist independently of differences in metabolic heat production per unit body surface area (BSA) between linemen and backs; and, 2) whether the specific combinations of on-field self generated air velocities, mean skin temperatures and ambient conditions affect heat balance parameters differently in these two positional groups during four key drill categories (special teams, wind sprints, individual drills and team drills). By fixing metabolic heat production per unit surface area in the first study it was possible to compare local sweat rates between position groups in a controlled environment whereby the heat balance requirements for evaporation were the same between groups [58], thus addressing a large limitation in previous research [30]. Furthermore, the second study facilitated an assessment of self-generated air velocities between position groups, which was previously hypothesized as a potential contributor to a higher core temperature in linemen compared to backs [26].

The present thesis presents two main conclusions. Firstly, despite exercising at a fixed metabolic heat production per unit BSA, linemen demonstrate significantly higher upper body local sweat rates (LSR) on the forehead, forearm, chest and shoulder. In addition, linemen also showed significantly larger increases in core temperature when compared to backs despite exercising at a much lower metabolic heat production per unit mass (L: 6.0±0.5 W/kg B: 8.2±0.8

W/kg). This observation suggests a greater heat storage per unit mass in linemen and therefore a diminished ability to dissipate heat, indicating that the proportion of sweat actually evaporating (sweating efficiency) from the surface of the skin must be much lower in linemen compared to backs. It was subsequently speculated that the lower sweating efficiency in linemen was due to a lower sweat gland density (SGD) [28] to the extent that the fraction of the skin surface that could be completely covered by sweat (skin wettedness) was reduced. In any given environment a reduction in maximal skin wettedness would lead directly to a lower maximal rate of evaporation (E_{max}) that would decrease the maximum compensable metabolic heat production in linemen, leading to a greater heat storage and greater increases in core temperature when compared to backs.

Secondly, when investigating differences in on-field self generated air velocities between linemen and backs, backs did show greater velocities during training camp practices as has been previously hypothesized [26], which resulted in significantly different heat transfer coefficients for both convection (h_c) and evaporation (h_e). However these differences when combined with similar observed skin temperatures and ambient conditions did not yield significant differences in either dry heat loss (C+R) or E_{max} between position groups by virtue of the non-linear relationship between both heat transfer coefficients and heat loss parameters (C+R and E_{max}). Specifically, large changes in h_{c_self} above values of ~10 W/(m^2•K) yield relatively small absolute changes in sensible heat loss. Likewise, large changes in h_{e_self} above values of ~150 W/(m^2•kPa) yield relatively small absolute changes in E_{max}. Nonetheless, despite no meaningful differences in dry heat loss or E_{max} (both per unit BSA) between positional groups, after accounting for the smaller BSA-to-mass ratio observed in linemen, the maximum rate of metabolic heat production per unit mass (W/kg) that could be physiologically compensable

(M_{max}) through combined dry and evaporative heat loss was ~20% lower in linemen compared to backs for all drills categories. Furthermore, if maximal skin wettedness was reduced in linemen as suggested by our first study, M_{max} was even lower in linemen compared to backs (~30%) for all drill categories.

3.2 Practical Considerations

This thesis provides practical considerations for both coaches and trainers of American football players. With the lower theoretical maximal skin wettedness seen in linemen compared to backs, the use of an external device, such as misting stations, to artificially increase skin wettedness in linemen may help to mitigate heat stress in this particular position group. Furthermore, any intervention aimed at increasing convection by eliciting a greater air velocity on the field (i.e. mechanical fans) may have a minimal influence on both convective and evaporative heat loss during on-field drills. However, these same interventions may be crucial during rest intervals or water breaks when players are standing still (v_{self} = 0). Finally, future interventions should focus on increasing rest intervals in order to decrease heat storage in both linemen and backs by minimize the total time spend at levels of uncompensable heat stress.

3.3 Conclusions and future research considerations

In summary, the present findings provide a novel contribution to the on-going study of why linemen experience greater elevations in core temperature during summer training camps when compared to backs. Our data support the idea that body morphology, specifically a large body surface area (BSA) and low BSA-to-mass ratio, may play the largest role in predisposing certain players (linemen) to higher levels of heat strain. A large BSA may contribute to a lower proportion of skin surface sweat coverage during maximal sweating secondary to a lower sweat gland density (study 1), and a low BSA-to-mass ratio leads to and a lower maximal compensable metabolic heat production (M_{max}) despite similar skin temperatures (study 2). A combination of these two factors would limit the work intensity that larger players can perform safely in the ambient environment typically present at a summer training camp. However, considering the intensity of competition at training camp, players would likely regularly exceed work rates that are physiologically compensable. Since there is no data currently available of actual on-field metabolic heat productions for linemen and backs, it remains unclear whether differences in the duration and intensity of metabolic heat production exist between positional groups.

Future research should focus on obtaining practical on-field measures of metabolic heat production in American football players in order to elucidate the compensability of position-specific demands for linemen and backs. This information could be used in planning practice schedules to ensure drills eliciting the highest metabolic heat productions are not placed in series. Furthermore, an actual measure of sweat gland densities (SGD) between linemen and backs should be performed in order to confirm the mechanism attributed to the lower observed sweating efficiency in linemen.

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