COMPARATIVE ANALYSIS OF PHYSIOLOGICAL MEASUREMENTS AND ENVIRONMENTAL METRICS ON PREDICTING HEAT STRESS RELATED EVENTS

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ABSTRACT

Comparative Analysis of Physiological Measurements and Environmental Metrics On Predicting Heat Stress Related Events

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Exposure to high heat and humidity can lead to serious health risks, including heat exhaustion and heat stroke. Wet Bulb Globe Temperature (WBGT) and heat index have historically been used to predict heat stress events, but individualized factors are not included in the measurement. It has been shown that there is a relationship between cardiovascular measurements and heat stress, which could be used to measure heat stress risk on an individual level. Research has been done to find relationships between cardiovascular metrics in a workplace environment, however the study did not include the use of a controlled environment as a baseline. This study provides measurements of transepidermal water loss (TEWL), heart rate, body core temperature, and blood pressure in a controlled environment when human subjects are exposed to high heat and humidity. Thirty subjects (n=17 females, 13 males) were asked to self-express their activity level (active vs. sedentary), gender, and age. The subjects performed a 30-minute moderate exercise routine on a stationary stepper machine in a heated environmental chamber (average WBGT of 26ºC). TEWL, heart rate, tympanic temperature, and blood pressure were recorded at every 10-minute increment of the exercise protocol per subject. The data was analyzed using JMP® software to find significant ($P<0.05$) relationships between the following factors and groups of subject characteristics: TEWL (activity level, gender, heart rate, systolic blood pressure, MAP, time, tympanic temperature); tympanic temperature (age, heart rate, time, TEWL); heart rate (age, time, tympanic temperature, TEWL). It is possible that an algorithm can be developed based on the relationships found between individualized metrics including TEWL, heart rate, blood pressure, and body core temperature to predict heat stress related events.

Key Words: Heat stress, transepidermal water loss, TEWL, arterial compliance, core temperature, heat exposure, wet bulb globe temperature, WBGT, heat stroke, heat exhaustion

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INTRODUCTION

1.1 Statement of Problem

There is a clinical need for an individualized method of predicting physiological heat stress to increase measurement accuracy and to take into account individualized factors that might be overlooked otherwise. Current methods of predicting heat stress are not ideal because they are based solely on environmental factors, without using individualized metrics. Early diagnosis of heat stress events has great potential to decrease occurrences of thermal discomfort, heat exhaustion, heat stroke, and heat-related fatalities.

1.2 List of Terms

Heat stress, transepidermal water loss (TEWL), arterial compliance, core temperature, body temperature, heat exposure, wet bulb globe temperature (WBGT), tympanic temperature, thermoregulation, heart rate, heat stroke, heat exhaustion

1.3 Purpose of Study

Exposure to high heat and humidity can lead to serious health risks, including heat stroke and other heat-stress related events. Wet Bulb Globe Temperature (WBGT) has historically been used to predict heat stress events, but individualized factors are not included in the measurement. It has been shown that there is a relationship between cardiovascular measurements and heat stress, which could be used to measure on an individual level. Research has been done to find relationships between cardiovascular metrics in a workplace environment, however the study did not include the use of a controlled environment as a baseline. Our study will provide measurements of Transepidermal Water Loss (TEWL), heart rate, body core temperature, and blood pressure in a controlled environment when humans are exposed to high heat and humidity to simulate a heat stress environment.

Chapter 2
STUDY SPECIFIC GOALS

The following is a list of study specific goals that were developed in order to effectively continue to collect meaningful results following previous researchers' experiments.

1. Measure physiological and environmental variables, including the following:
    - TEWL with Delfin Vapometer™
    - Heart rate and blood pressure with Omron 5-Series Upper Arm Blood Pressure Monitor™
    - Wet Bulb Globe Temperature (WBGT) with ThermoPro Indoor Humidity and Temperature Monitor™
    - Body core temperature estimate with Braun ThermoScan 5™ infrared tympanic thermometer
2. Characterize above variables in a controlled environment as subjects are exercising:
    - Cal Poly environmental chamber set-up with heater and vaporizer
    - The chamber temperature set between 80 and 90ºF, and the maximum relative humidity of approximately 70% (corresponding to a WBGT of approximately 27.5ºC)
    - Exercising activity using a stationary step climber at the activity level set by the subject
3. Compare physiological and environmental measurements using acceptable and representative statistical techniques

Chapter 3

BACKGROUND

3.1 The Dangers of Heat Stress

Heat stress is often an overlooked hazard that can become lethal if precautionary steps are not taken, including hydrating and taking rest breaks when appropriate. Some people are more at risk of heat stress based on occupation, residence, and activities, like playing sports. In addition, climate change and heat waves pose a threat and contribute to over 150,000 heat-related deaths annually, according to the World Health Organization (Patz JA, 2005). According to the Environmental Protection Agency (EPA), over 9,000 deaths have occurred since 1979 in the United States due to heat exposure, with a peak in 2006 (EPA, 2016). With ongoing heat wave occurrences and heat stress related events, heat-related deaths will continue to be a consequence. Heat stress is categorized into heat exhaustion and heat stroke based on the types of symptoms faced. Heat exhaustion symptoms include dizziness, headaches, fainting, vomiting, and weakness, whereas heat stroke symptoms can include seizures, convulsions, unconsciousness, mental confusion, and hot, dry skin without sweating. Existing methods for predicting heat stress events are based solely on environmental metrics, which generates a clinical need for an individualized method that brings physiological factors into effect.

3.2 Heat Stress Index and Wet Bulb Globe Temperature

Temperature and relative humidity are factors that estimate the heat index (HI), or sometimes called heat stress index, which is used to predict the risk of physiological heat stress for an average individual (“Heat (stress) Index”, 2017). Humidity affects the body's ability to regulate internal heat through perspiration (evaporation of water that diffuses through the skin). The body feels warmer when it is humid because sweat evaporates more slowly off the skin, and at high enough levels, sweating seizes and body temperature continues to heat up. With higher temperature, the air can hold more water vapor and the surface temperature increases, making the atmosphere warmer and more humid, thus raising the HI (Deaths, 2014). There are many

physiological consequences of high heat stress index. At HI of 90–105°F (32–41°C), for example, sunstroke and heat exhaustion are possible consequences after extreme heat exposure (Deaths, 2014).

Heat stress screening and monitoring of football players, firefighters, soldiers, and others at risk is an established preventative action that has been done for decades. However, there are no standards of how heat stress affects factors of individual physiology and acclimatization. Wet bulb globe temperature (WBGT) is often used to predict physiological heat stress for any individual, like heat index, but WBGT is calculated based on temperature, humidity, wind speed, sun angle and cloud cover (National Weather Service). The WBGT formula is based on three factors: wet bulb temperature measuring effect of humidity (T_w), black globe temperature measuring solar radiation (T_g), and dry bulb temperature measuring ambient air temperature (T_d) (Korey, 2017). The equations used to calculate WBGT while outdoors with solar loading (Equation 1) and when indoors or outdoors with no solar loading (Equation 2) are as follows:

$$WBGT = 0.7 + T_w + 0.2T_g + 0.1T_d \qquad (1)$$

$$WBGT = 0.7 + T_w + 0.3T_g \qquad (2)$$

All temperature variables must be inputted in either centigrade or Fahrenheit, which gives two different heat category tables for WBGT depending on the chosen temperature unit. A WBGT measurement of greater than 82°F, or 28°C, corresponds to a very high heat risk, which is one of four heat risk categories established by the International Association of Athletics Federations. The original application of WBGT was for military trainees who only wear shorts and a t-shirt, so for those wearing heavier clothing, the WBGT must be adjusted. For example, football players wear heavy gear that restricts sweat evaporation, compromising the heat loss process, because the gear itself increases the WBGT by 10°C (Bishop, 2017). WBGT risk for running is summarized in the following table:

Table 1. Wet Bulb Globe Temperature Risk For Running Adapted From Roberts (1998)

WBGT	***Level of Risk***
<18°C	Low
18°C-23°C	Moderate
23°C-28°C	High
>28°C	Extreme

There are several differences between HI and WBGT measurements as environmental health parameters. Heat index is an "apparent temperature" measurement made assuming a person is walking at 3 mph in a shady environment, or without full sunlight exposure (Korey, 2017). These assumptions do not take into account other exercises, like running, or activities outside. Furthermore, there are over 20 different algorithm alternatives currently used to calculate HI, which are mostly based on Steadman's apparent temperature indices (Anderson, 2013). Despite the common usage of WBGT and HI for environmental health research, neither WBGT nor HI are individualized measurements for predicting physiological heat stress. Thus it can be argued that there is a clinical need for an individualized method of predicting physiological heat stress to increase measurement accuracy and to take into account individualized factors that might be overlooked otherwise.

3.3 Thermoregulation

Physiological factors, not just environmental factors, are known to affect the occurrence of heat stress related events. One's ability to adapt to heat decreases due to increasing age, being ill, and low levels of physical activity. Body core temperature can fluctuate based on age, gender, medications, and cardiovascular health (Ramphal-Naley, 2012). Heart rate, stroke volume, blood pressure and arterial compliance change as the intensity of heat stress increases, from heat oedema to heat stroke. During exercise, the body's thermoregulation process is essential to avoid over-heating and permit heat-stress related events. Some energy is exchanged between the body and the environment in the form of mechanical work (about one fourth of

metabolic energy), but most energy (remaining three fourths or more) is exchanged as heat (Wenger, 1999). When the energy produced during exercise and the energy acquired by the environment does not add up to the net energy lost, the excess heat is either stored in the body's core or lost from the body. Wenger summarizes the heat balance equation as

$$M = E + R + C + K + W + S \qquad (3)$$

where M is metabolic rate, E is rate of heat loss by evaporation, R and C are rate of heat loss by radiation and convection, respectively, K is rate of heat loss by conduction, W is rate of energy loss as mechanical work, and S is rate of heat storage in the body. If S is positive, the mean body temperature is increasing. As exercising muscles produce heat, the blood that perfuses through the muscles travels to the body core, which warms the core and eventually the rest of the body via convection. Most heat that is exchanged with the environment is through the skin. Convective heat exchange between skin and air is proportional to the surface area of skin and the difference between the temperature of the ambient air and skin. Relative humidity represents the moisture content of air as the ratio between actual moisture content of air and the maximum moisture content allowed at the temperature of the air (Wenger, 1999).

To dissipate the heat produced during exercise, the body responds in a series of steps, first by increasing the rate of sudomotor and vasomotor activities. The dominant sudomotor activity that takes place is sweating, while vasomotor activities promote the increase of skin blood flow (SkBF) and dilation of superficial veins (Gisolfi, 1984). While sweating, SkBF delivers heat produced by the act of exercising from the body's core to the skin, where sweat is evaporated into the environment. The core of the body includes the cranial, thoracic, and abdominal cavities, from which thermodetectors in the spinal cord and anterior hypothalamus signals for increased SkBF (Anderson, 2013). Superficial arteries dilate, or expand, when the core temperature warms to allow for greater efficiency of heat convection by SkBF.

In a review article written by J. Werner, the human body's temperature regulation mechanism is simplified into three autonomic effector mechanisms: metabolic heat production (i.e. shivering), sweat production with evaporation and vasomotor action (vasoconstriction or

vasodilation), and various behavioral effector actions (i.e. removing clothing or physically moving to a cooler environment) (Werner, 2010). Werner also mentions the importance of considering that temperature regulation acts as a feedback control-loop with two subsystems – called "processors" and "process" – as represented in Figure 1. The loop represents body temperature, T_b, as the output of a heat transfer "process" acted on by ambient temperature, T_a. Body temperature is sensed by thermosensors, central controllers, and effectors, which make up the "processors" and activate effector mechanisms, EM. Werner goes on to explain that the simplified, two-system loop represents a negative feedback loop, meaning that as body temperature increases or decreases (caused by ambient temperature, for example), one or more effector mechanisms must be activated to counter the change in body temperature. If body temperature increases due to heat, vasodilation would increase as well as sweat production to counteract the change in body temperature.

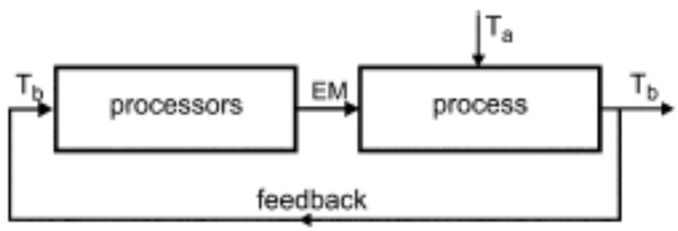

Figure 1. Thermoregulatory Control-Loop (Werner, 2010).

During enhanced heat stress episodes, the body must adapt to the excess heat and fluid loss within the body's core in order to minimize health risks, such as impairment of venous return and diastolic filling of the heart. Fluid loss (caused by peripheral pooling of blood and decreased plasma volume) is compensated by constriction of the renal and splanchnic vascular beds, which allows for more cardiac output perfusion of muscle during exercise. The decrease in blood flow through these beds restores, partially, the central blood volume and cardiac diastolic filling, acting to maintain cardiovascular homeostasis. However, when cardiovascular strain is too high for the skin blood flow mechanism to maintain cardiac filling, skeletal muscle rhythmically contract to move venous blood toward the heart in order to compensate (Werner, 2010). These contractions over time lead plasma volume to decrease and in result increase heart rate and myocardial

oxygen demand (Jacklitsch, 2016). Core body temperature begins to increase in these conditions, as well as when the body is dehydrated from sweating or when a significant amount of blood is redistributed to muscles and the cutaneous circulation, which acts to lose heat from the body. In theory, the skeletal muscles during exercise and the skin compete for the available cardiac output, from which the heart cannot meet the demands of – this leads to cardiovascular strain. Since cardiovascular strain results prior to exhaustion during intense whole-body exercise and environmental heat stress, there is potential to predict when a heat stress event will occur (Rowell, 1974). Influential researchers in this field, including LB Rowell, have continued to explore the details of thermoregulation during heat stress. This study is an attempt to continue his and others' studies to understand the complexities of the human body.

3.4 Core Body Temperature Measurement

Measuring body temperature is one of the oldest methods used to test an individual's health. To date there are several methodologies of clinical thermometry that give body temperature estimates. Mercury-in-glass thermometers were the gold standard for reading body temperature, but this method is deemed hazardous due to the mercury contents which poses a serious health risk. Non-invasive, mercury-free clinical devices used for measuring body temperature have emerged in the market, including electronic contact, chemical, and infrared-sensing thermometers (Davie, 2010). These thermometers are sensitive to the site of measurement, time of day during measurement, age, gender, and any recent activity performed by an individual. Other thermometry methods are more invasive than others, which is an important factor when determining what to use in a non-clinical setting. Pulmonary artery catheters and rectal thermometers are two such examples of invasive thermometry methods. Pulmonary artery catheters are common tools for measuring core body temperature, which typically falls within the range 37.35±0.6°C (Davie, 2010). The normal rectal temperature range, which is another common method for measuring body core temperature, is 36.1±1.7°C (Davie,

2010). This range is much larger compared to that of the pulmonary artery catheter normal temperature range, but is still commonly used today.

A practical, non-invasive method for measuring core body temperature is necessary for predicting heat stress events. Infrared-sensing ear thermometers, also referred to as tympanic thermometers, have been heavily studied for clinical use, especially as an estimator for body core temperature. The thermometer detects infrared energy that emanates from the ear canal and tympanic membrane, which are detected in only a few seconds once the thermometer tip enters the opening of the canal. It is believed that there exists a correlation between tympanic temperature and body core temperature because the tympanic membrane in the ear shares the same blood supply with the hypothalamus in the brain, which is the body's temperature control center. The maximum permissible error for tympanic thermometers is ±0.2°C with a range of 35.5-42.0°C, as governed by International Standard BS EN 12470, with user-dependent errors included in the standard (Davie, 2010). In Sudan, a study was done by Gasim *et al* to research the accuracy of tympanic thermometers compared to temperature obtained by conventional yet risky mercury-glass thermometers. The mercury-glass thermometers measured axillary temperature which is known to correlate to rectal temperature, a common estimate for body temperature. Axillary temperature is measured by placing a mercury bulb thermometer in a person's axilla (or armpit) for at least 5 minutes, which takes much longer than a standard tympanic thermometer. Tympanic thermometers have several advantages in thermometry because the site of measurement is non-invasive and is quick to read compared to most other methods. The study results provided evidence that tympanic thermometers are as reliable and accurate as axillary mercury glass thermometry (Gasim, 2013). Whether in a home, clinical, or heat stress environment, using a tympanic thermometer is an easy, fast way to determine whether someone is at risk for a heat stress event.

3.5 Renin-Angiotensin Pathway During Heat Stress

One theory to explain decreased thermoregulation while sweating is due to secretion of renin. Renin is an enzyme produced by the kidney when blood pressure is decreased and blood flow is insufficient. As plasma sodium and plasma volume decreases, juxtaglomerular cells present in the kidney secrete renin, which converts angiotensinogen into angiotensin I, and eventually is converted to angiotensin II. Angiotensin II acts to increase blood pressure, cardiac output, and systolic blood pressure via vasoconstriction of venular and arteriolar smooth muscle, leading to decreased thermoregulation. The adrenal cortex secretes aldosterone in response to angiotensin II levels, which acts to reabsorb Na^+ ions and water in tubules of the kidney, which are lost during sweating, to increase blood volume and systolic blood pressure. A research study was done to research the effects of heat stress induced by a sauna bath on heart rate, systolic blood pressure, and diastolic blood pressure. This study's results showed that heart rate and systolic blood pressure increased during the first 10 minutes of exercise and then decreased over time thereafter. Also, plasma renin activity (PRA) and angiotensin II levels were highest after 20 minutes of exercise, whereas aldosterone concentration was a maximum at 30 minutes after the heat stress. PRA may have increased (as in this study) because concentrations of catecholamines, which are stimulators of renin secretion, increase during heat stress (Kosunen, 1976). The change in PRA and angiotensin II levels during exercise may coincide with a change in arterial compliance, a metric relating change in arterial volume with change in arterial pressure. A pattern of increasing arterial compliance during heat stress could be explained by the renin-angiotensin system.

In another study, Kotchen *et al*. measured changes in PRA, plasma norepinephrine (NE), and epinephrine (E) levels in 6 healthy subjects during graded exercise on a bicycle ergometer over 30 minutes (Kotchen, 1971). The results suggest that renal blood flow is dependent on exercise intensity. Figure 2 from the study suggests an explanation for the relationship of PRA and exercise. With exercise, circulating catecholamines and renin activity were shown to increase, as also shown in the results of the sauna bath study. During heat stress, the body secretes renin in order to bring the body back to equilibrium. Because renin secretion works to

reabsorb sodium and water that would otherwise be lost as sweat, an increase in body core temperature consequently may be suspended during heat stress. This pattern is one theory used to explain the delayed increase in core body temperature as found in similar studies, and it could help determine a more accurate model of physiological changes during heat stress.

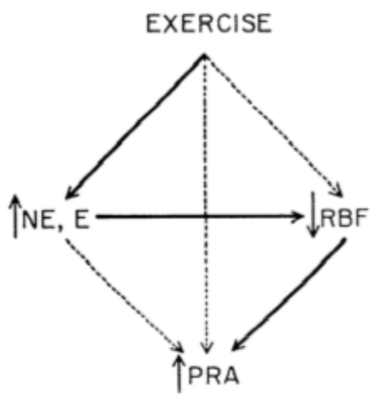

Figure 2. Suggested Mechanism for PRA Response to Exercise. The dotted arrows are meant to indicate the cause and effect relationship may be dependent on one intermediate variable or two variables represented by the darker arrows. Figure from Kotchen (1971).

3.6 Exercise Induced Heat Stress

A study by Wesley K Lefferts *et al* examined the vascular effects of exercise-induced heat stress (EIHS) on firefighters (Lefferts, 2015). The gear firefighters wear, as well as the physicality of the job and the heat they are exposed to helps explain the high mortality rate of firefighters compared to other occupations. Between 1977 and 2002, around 45% of firefighter line-of-duty deaths occurred each year due to coronary heart disease (CHD) (Bishop, 2017). Among other professions, including police and detectives, as well as emergency medical service workers, CHD accounted for much fewer on-duty deaths: 22% and 11% respectively. Fatalities

were high in 2016 as well, with 89 firefighters killed on the job, with 40 fatalities due to heart attacks (National Safety Council, 2017). Poor cardiovascular health continues to be the leading cause of death among the profession, which has been repeatedly studied in an attempt to lower the statistic. Stress, overexertion, and fluid-loss all participate in creating the fatal consequences of firefighting. EIHS is accepted to have physiological effects on the human body, including a decrease in total peripheral resistance (or resistance to blood flow). This change ultimately leads the body to increase cardiac output in an effort to stabilize arterial blood pressure. Usually this is done by increasing heart rate and cardiac inotropic properties and results in an escalation in cardiovascular strain (Ganio, 2010). The results of the study by Lefferts *et al* explained that moderate EIHS leads to increased myocardial work and reduced coronary perfusion (Lefferts, 2015). This biological response is thought to be a reaction to a deficiency in oxygen supplied versus oxygen demanded developed over time in a heat stress environment. The imbalance of myocardial oxygen supply and demand found in the study suggests that EIHS can increase sudden cardiac event risk. In order to minimize sudden cardiac events, biological knowledge of arterial compliance can be applied to experimental results in a controlled environment, which has potential to make a radical clinical impact.

3.7 Heat Stress Physiological Model

Because physiological metrics such as body core temperature, arterial compliance (the inverse of arterial stiffness), heart rate, and blood pressure all work together to attempt to keep the body in homeostasis, there is potential for the development of a physiological model to relate these metrics to environmental metrics. Relationships between transepidermal water loss (TEWL) and cardiovascular metrics have been assessed in high heat risk environments. In a study by Michael D. Whitt *et al*. 24 subjects were observed exercising over a period of 30 minutes in a high heat environment, with WBGT of 27.5°C (Whitt, 2008a). The purpose of the study was to investigate a potential relationship between gender, age, or activity-level with TEWL, as well as a relationship between TEWL and cardiovascular metrics. TEWL is a measurement that provides

sweating rate information taken from the skin surface. The results concluded that gender did not play a role in the relationship with TEWL. Also, heart rate, elapsed time of exercise in a heat stress environment, and age had a significant effect on TEWL ($P<0.05$). Researchers have discovered a pattern of delayed increase in body core temperature and a decrease in blood pressure at the beginning of exposure to heat stress. Relative changes in arterial compliance, heart rate, TEWL, and/or changes in oscillometric blood pressure measured during the beginning of the onset of heat stress could reveal undiscovered patterns leading to an increase in body core temperature.

The ultimate intent of this study was to continue the experiment performed by Whitt *et al*. by testing the hypothesis that within a high heat risk environment, there exists a relationship between the environment and individualized physiological measurements that can be used to prevent heat-related events from occurring, which can be represented with a physiological model. Whitt *et al*.'s previous studies have reported the following results from experimental studies that measure physiological changes in a high heat risk environment:

(1) Elapsed time has a significant effect on diastolic pressure and heart rate (Whitt, 2008a).

(2) The magnitudes of diastolic pressure, systolic pressure, and heart rate mean changes over time are all directly correlated with a maximum reached at the elapsed time of 20 minutes (Whitt, 2008b). This was also found in another study, with the addition of a slight mean decrease at the 30 minute mark (Whitt, 2008a).

(3) A direct correlation exists between TEWL and heart rate in result to increased sympathetic nervous system activity (Whitt, 2008a).

(4) Activity level has a significant effect on TEWL, with a decreased TEWL rate seen in subjects over 25 years old (Whitt, 2008a).

In this study, physiological measurement changes will be ascertained and compared to appropriate environmental metrics. A model that includes individualized metrics, not just environmental metrics, could lead to a more exact heat strain measurement to predict an

oncoming heat illness episode. It can be argued that a noninvasive method for predicting heat illness has a clinical need, especially for those vulnerable and susceptible to high heat and humidity environments.

Chapter 4

METHODS AND EXPERIMENTAL PROCEDURES

The research methodology was adapted from previous studies by Whitt *et al*. to continue research to identify possible relationships between more varieties of physiological measurements involved with body thermoregulation during heat stress. The Cal Poly Institutional Review Board (IRB) approved this study's protocol as described in this chapter in April 2018.

4.1 Subject Identification and Recruitment

The subjects included were taken from a convenience sample of students at Cal Poly. According to the Central Limit Theorem, a maximum of 30 students was needed in the study to represent the population. Potential subjects were excluded from the study if they had a history of heat-related illness, recent surgical procedure, exercise-induced asthma, high blood pressure, cardiac related problems, or are pregnant. Also, each potential subject's body mass index (BMI) was calculated during the screening process in order to reject any subject who's BMI did not fall into the "Healthy Weight" BMI category of the Adult BMI Chart released by the US Department of Health and Human Services, as shown in Figure 3. The factors and levels listed in Table 2 were recorded before the experiment started and were used to classify all subjects. These factors and levels make up the inclusion criteria. The symptoms and correct treatment of heat cramps, heat syncope, heat exhaustion, and heat stroke, as listed in Table 3, were known to the study investigators in order to make sure the subjects were given appropriate medical help if needed (Newsham, 2002).

BMI	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35
Height									Weight in Pounds								
4'10"	91	96	100	105	110	115	119	124	129	134	138	143	148	153	158	162	167
4'11"	94	99	104	109	114	119	124	128	133	138	143	148	153	158	163	168	173
5'	97	102	107	112	118	123	128	133	138	143	148	153	158	163	168	174	179
5'1"	100	106	111	116	122	127	132	137	143	148	153	158	164	169	174	180	185
5'2"	104	109	115	120	126	131	136	142	147	153	158	164	169	175	180	186	191
5'3"	107	113	118	124	130	135	141	146	152	158	163	169	175	180	186	191	197
5'4"	110	116	122	128	134	140	145	151	157	163	169	174	180	186	192	197	204
5'5"	114	120	126	132	138	144	150	156	162	168	174	180	186	192	198	204	210
5'6"	118	124	130	136	142	148	155	161	167	173	179	186	192	198	204	210	216
5'7"	121	127	134	140	146	153	159	166	172	178	185	191	198	204	211	217	223
5'8"	125	131	138	144	151	158	164	171	177	184	190	197	203	210	216	223	230
5'9"	128	135	142	149	155	162	169	176	182	189	196	203	209	216	223	230	236
5'10"	132	139	146	153	160	167	174	181	188	195	202	209	216	222	229	236	243
5'11"	136	143	150	157	165	172	179	186	193	200	208	215	222	229	236	243	250
6'	140	147	154	162	169	177	184	191	199	206	213	221	228	235	242	250	258
6'1"	144	151	159	166	174	182	189	197	204	212	219	227	235	242	250	257	265
6'2"	148	155	163	171	179	186	194	202	210	218	225	233	241	249	256	264	272
6'3"	152	160	168	176	184	192	200	208	216	224	232	240	248	256	264	272	279
	Healthy Weight						Overweight					Obese					

Source: US Department of Health and Human Services, National Institutes of Health, National Health, Lung, and Blood Institute. The Clinical Guidelines on the Identification, Evaluation and Treatment of Overweight and Obesity in Adults: Evidence Report. September 1998 [NIH pub. No. 98-4083].

Figure 3. Adult BMI Chart. Subjects with a BMI between 19 and 24 were only included in the study (American Cancer Society, 2018).

Table 2. Subject Inclusion Criteria.

Factor	*Levels*
Gender	Male Female
Age	18-25 years old >25 years old
Self Expressed Activity Level	Active Sedentary

Table 3. Evaluation and Initial Care of Heat Illness adapted from Newsham *et al*. (2002)

Heat Illness	***Signs and Symptoms***	***Treatment***
Heat cramps	Painful cramping of abdomen and extremities caused by intense prolonged exercise in the heat. Associated with fluid/electrolyte imbalance.	Stop exercise. Replace fluids and electrolytes orally.
Heat syncope	Weakness, fatigue, thirst, and fainting due to exercise in heat and fluid/electrolyte imbalance. Predisposes athlele In heat stroke.	Stop exercise. Move to cooler environment; begin oral replacement of fluids and electrolytes.
Heat exhaustion	Profound weakness, exhaustion, tremendous thirst, nausea, vomiting, headache, dizziness, profuse sweating, elevated body temperature (<40°C). Also, chills, hyperventilation, loss of coordination, irritability, syncope, confusion. Acute stages may include low blood pressure and elevated pulse rate.	Stop exercise. Move to cooler environment; remove equipment and cool victim with fanning and ice packs/cool water showers. Athlete should not return to activity for remainder of that day (minimum).
Heat stroke	As in heat exhaustion, but also neurologic disability; signs of central nervous system dysfunction, and elevated body temperature (>41°C). Contrary to previous beliefs, victims of exertional heat stroke may present with perspiration, not dry skin. Seizure and coma are possible.	THIS IS A MEDICAL EMERGENCY. DELAY COULD BE FATAL. Remove wet or heavy clothing. Begin whole body cooling with water immersions, vigorous fanning, ice packs applied to neck, groin, and underarm. Do not use methods that inhibit other medical procedures such as cardiopulmonary resuscitation. Continue to monitor body temperature until emergency medical service arrives; do not cool below 39°C.

Table 4. Experimental Subject Information.

Subject #	***Gender***	***Activity Level***	***Age***
1	F	Active	22
2	F	Active	23
3	F	Active	21
4	M	Active	23
5	M	Active	23
6	M	Active	22
7	F	Active	23
8	M	Active	18
9	F	Sedentary	23
10	F	Sedentary	23
11	F	Active	20
12	F	Active	23
13	F	Sedentary	24
14	M	Active	19
15	M	Active	20
16	F	Active	22
17	M	Sedentary	18
18	M	Sedentary	21
19	M	Active	20
20	F	Active	22
21	M	Active	52
22	M	Active	36
23	F	Sedentary	23
24	M	Active	32
25	F	Active	21
26	M	Active	54
27	F	Active	20
28	F	Active	21
29	F	Active	64
30	F	Active	22

4.2 Pre-Exercise Protocol

4.2.1 Heart Rate Measurement

Using the recorded age of each subject, their maximum normal heart rate (bpm) during exercise was calculated using the following equation, where age is in years (AHA, 2018):

$$220 - Age \ = \ Maximum\ Heart\ Rate \qquad (4)$$

The maximum heart rate during exercise was calculated per subject to be used as an indicator to stop the experiment. The Omron automated blood pressure unit (Model BP742) provided average pulse per subject, which was documented before and during every 10-minute increment of the experiment. The Omron monitor was also used as a detector of an irregular rhythm. An irregular heartbeat symbol would appear on the monitor's display with the irregular blood pressure measurement values. An irregular heartbeat rhythm is defined as a rhythm that is 25% less or 25% more than the average rhythm detected while the monitor is measuring the systolic and diastolic blood pressure. The experiment was discontinued if a subject's heart rate reached above 85% (shown in Table 4) of their calculated maximum exercising heart rate, or when the irregular rhythm symbol was displayed by the Omron device (which ever came first).

Table 5. Average Maximum Heart Rate Guide (AHA, 2018).

Age	Target HR Zone 50-85%	Average Maximum Heart Rate, 100%
20 years	100-170 beats per minute (bpm)	200 bpm
30 years	95-162 bpm	190 bpm
35 years	93-157 bpm	185 bpm
40 years	90-153 bpm	180 bpm
45 years	88-149 bpm	175 bpm
50 years	85-145 bpm	170 bpm
55 years	83-140 bpm	165 bpm
60 years	80-136 bpm	160 bpm
65 years	78-132 bpm	155 bpm
70 years	75-128 bpm	150 bpm

4.2.2 Core Body Temperature Measurement

Initial core body temperature was measured using an infrared tympanic thermometer (Braun Thermoscan) while the subject was in the ambient room. To get estimates of body core temperature, tympanic temperature was measured by exposing the opening of the subject's right ear to an infrared imaging thermometer. Each subject received their own disposable cover placed on the thermometer before taking tympanic temperature measurements. If the body temperature increased greater than 1.5ºC above the initial recorded body temperature during any part of the

experiment, the subject would not perform any further tests in order to minimize potential health risks. A similar study by Newsham *et al*. also stopped subjects from exercise once core body temperature increased by 1.5ºC during the experiment (Newsham, 2002).

4.2.3 Sweat Rate (TEWL) Measurement

Using the left upper arm, a VapoMeter™ was placed on the skin surface of each subject to measure TEWL, which took place between 7 and 16 seconds to complete the measurement. The Delfin Vapometer™ is able to measure TEWL, a skin barrier property, by sensing an increase in relative humidity on the skin. The chamber within the device is sealed off from the ambient air during the measurement, which allows the sensor to detect the relative humidity of the skin. TEWL is defined as flux density of condensed water evaporating off the skin in units of ($\frac{g}{m^2h}$), also known as evaporation flux.

4.2.4 Arterial Compliance Measurement

Arterial compliance was planned to be measured for each subject; however due to unexpected circumstances, this measurement was not included in this study. An occlusive arm blood pressure cuff technique referred to as Calibrated Cuff Plethysmography (CCP) would have been used to gather arterial compliance data. The right upper arm of each subject would have been marked with a Sharpie marker in order to apply the cuff at the same location with the same tightness for each blood pressure measurement, which should have placed the bottom of the cuff about ½ inch above the right elbow. The equipment used for this measurement would have consisted of using a BIOPAC MP160 system with an amplifier (Model DA100), pressure transducer (Model TSD104), a blood pressure cuff, and AcqKnowledge software. While the cuff was around a subject's upper right arm, a manual bulb would have been used to fill the blood pressure cuff to 100 mm Hg and held for 30 seconds before allowing the pressure to drop to 0 mm Hg. AcqKnowledge would have been used to collect and display the arterial pressure pulse data used to calculate arterial compliance per individual.

4.2.5 Blood Pressure Measurement

The Omron device was used to measure blood pressure at the same location as with the CCP method. Regarding blood pressure, the American Heart Association (AHA) states that a drop of greater than 10 mm Hg/MET for systolic blood pressure during exercise is an indication to stop exercise, where MET stands for Metabolic Equivalent (Fletcher, 2013). AHA states in the article "a normal systolic blood pressure response to progressive exercise is dependent on both sex (higher in males) and age (higher with advancing age). The average rise in systolic blood pressure during a progressive exercise test is about 10 mm Hg/MET." If a subject's difference in systolic blood pressure from initial blood pressure reading to any point in exercise was greater than 30 mm Hg (assuming an MET of 3 for the exercise protocol in this study), the subject was instructed to step out of the chamber and the experiment would stop. Changes in systolic blood pressure were successfully recorded with the Omron device.

4.3 Exercise in Chamber Protocol

The exercise portion of the experiment took place in an environmental chamber in Building 38 room 133 on the Cal Poly campus. The chamber was set to a temperature and humidity greater than ambient conditions. The maximum temperature was held constant at approximately 80-90ºF, and the maximum relative humidity was approximately 70% corresponding to a WBGT of about 27.5ºC as used in a similar study by Newsham *et al*. These settings were previously used to safely perform experiments on ten subjects (six males and four females) with an average age of 28 (Newsham, 2002). Also, temperature and humidity were measured in the chamber as well as in the ambient room at the start of the experiment and observed periodically during the experiment. The temperature and relative humidity readings were measured by a ThermoPro TP-55 Indoor Humidity and Temperature Monitor.

Following the pre-exercise measurements being taken as mentioned above, the subject was then ready to enter the temperature and humidity controlled chamber. Upon entering the room, the subject began stepping up and down on a step that is less than twelve inches high

while performing optional simultaneous arm curl motions. The stepper exercise machine manufactured by “Sunny Health and Fitness” is shown in Figure 4. Each subject exercised at a self-selected intensity and and was encouraged to exercise at an aerobically challenging pace. Water was made available to the subject whenever desired. Additionally, the subject was instructed to stop whenever the discomfort was perceived to be too significant. At the end of 10, 20, and 30 minutes of exercise, the subject stepped out of the chamber, and measurements for TEWL, blood pressure, and heart rate were taken and recorded. The temperature and humidity values of the chamber were recorded during each 10 minute increment throughout the experiment.

Figure 4. “Sunny Twister Stepper with Handle Bar”

Manufactured by Sunny Health and Fitness.

4.4 Calculating Arterial Compliance

Arterial compliance is an important physiological measurement that quantifies how much a blood vessel wall can expand and contract passively. To view changes in arterial compliance, an arterial compliance curve can be used to view arterial compliance as a function of transmural

pressure, or the difference between the intralumen arterial pressure and the external pressure applied to an artery. Arterial compliance can be estimated by measuring the magnitude changes of each individual's peak to peak amplitudes of the arterial waveform generated from band pass filtered data. The software called AcqKnowledge has the ability to collect and display the peak to peak amplitudes collected by the BIOPAC system. The band pass filtered data would be used to calculate the change in arterial pressure by measuring the peak to peak amplitudes. Shown below are the variables needed to calculate arterial compliance, or $(dV/dP)_{artery}$ (see Equation 5) (Whitt, 1999).

- $dP_{artery\ at\ cuff}$ is the magnitude of arterial pressure pulse measured at the cuff (mm Hg)
- $dP_{pump\ at\ cuff}$ is the magnitude of the pump pressure pulse measured at the cuff (mm Hg)
- $dV_{pump\ at\ cuff}$ is the pump stroke volume at system pressure (ml)
- Systolic and diastolic pressures were obtained via oscillometry

$$\left(\frac{dV}{dP}\right)_{artery} = dP_{artery_{at\ cuff}} * \left[\frac{\left(\frac{dV}{dP}\right)_{pump_{at\ cuff}}}{P_{Systolic} - P_{Diastolic}}\right] \qquad (5)$$

4.5 List of Equipment

- ThermoPro Model No. TP-55: Indoor Humidity and Temperature Monitor
- Delfin Vapometer™
- Urpower Humidifier Model No. MH-501
- Omron Automated Blood Pressure Unit Model BP742
- Braun ThermoScan 5 Ear Thermometer
- BIOPAC MP160 System (to use in future studies)

- Pressure Transducer Model TSD104
- Amplifier Model DA100
- Blood Pressure Cuff
- AcqKnowledge Software

4.6 Ethical Considerations

The study's protocol and informed consent form were approved by the Cal Poly IRB Committee on April 6, 2018. Confidentiality of all subject data is protected, as their names and personal information will never be written in anything other than the written consent form. All screened subjects had the capacity to give informed consent.

Chapter 5

RESULTS

After data collection, mean arterial pressure (MAP) was calculated using Equation 6 (Whitt, 1999) shown below:

$$MAP = BP_{Diastolic} + \frac{1}{3}(BP_{Systolic} - BP_{Diastolic}) \qquad (6)$$

MAP is thought to be the average pressure in the arteries during one cardiac cycle, representing another useful factor for an individualized model.

The data collected from a sample size of 30 subjects (n=17 females, 13 males) following the protocol described in *Chapter 4: Methods and Experimental Procedures* were transferred to JMP® software for statistical analysis. The summarized results are shown in Table 6. Table 7 summarizes the arithmetic means of each factor at 0, 10, 20, and 30 minutes of exercise with corresponding P-values from linear regression tests completed in JMP®.

Two independent factors—age and diastolic blood pressure—were found to have no significant effect on TEWL at a 95% confidence interval. The following independent factors were found to have a significant effect on TEWL at a 95% confidence interval:

- Heart rate
- Time
- Activity level
- Tympanic temperature
- Gender
- Systolic blood pressure
- Mean arterial pressure

Four independent factors—gender, activity level, diastolic and systolic blood pressure—were found to have no significant effect on tympanic temperature at a 95% confidence interval. The following independent factors were found to have a significant effect on tympanic temperature at a 95% confidence interval:

- Heart rate
- Time
- TEWL
- Age
- Mean arterial pressure

Table 6. Summary of Environmental and Physiological Calculations For All Factors And Levels.

Factor (Level)	***N (# of data samples)***	***Systolic BP (mm Hg)***	***Diastolic BP (mm Hg)***	***Mean arterial BP (mm Hg)***	***Heart Rate (BPM)***	***TEWL (g/m^2h)***	***Tympanic Temp (C)***	***Chamber WBGT***
Time (0 minutes)	30	127.7 ±14.0	74.8 ±10.4	92.4 ±8.8	71.2 ±15.5	10.0 ±6.6	97.9 ±0.8	25
Time (10 minutes)	30	140.6 ±16.2	76.4 ±10.0	97.8 ±9.5	88.8 ±25.9	54.8 ±44.7	98.7 ±0.7	26
Time (20 minutes)	30	131.7 ±19.6	74.5 ±8.8	93.6 ±10.4	97.1 ±26.8	95.3 ±52.4	99.1 ±0.8	26
Time (30 minutes)	30	140.2 ±13.8	81.3 ±14.9	100.9 ±12.6	102.5 ±25.7	115.2 ±54.9	99.2 ±0.7	26
Gender (Male)	52	142.4 ±16.5	72.5 ±9.7	95.8 ±10.3	85.8 ±24.9	83.8 ±69.5	98.6 ±0.9	26
Gender (Female)	68	131.4 ±15.6	80.3 ±11.1	97.3 ±10.8	92.6 ±27.4	54.6 ±46.7	98.7 ±0.9	26
Activity Level (Active)	96	138.3 ±17.4	77.7 ±11.2	97.9 ±10.5	89.0 ±27.1	74.5 ±62.0	98.7 ±0.9	26
Activity Level (Sedentary)	24	125.9 ±9.0	74.5 ±11.0	91.6 ±9.1	93.5 ±24.0	37.7 ±31.9	98.7 ±0.8	26
Age (>25 years old)	20	146 ±19.8	80.7 ±9.4	102.5 ±10.4	70.5 ±14.6	77.0 ±67.1	98.2 ±0.8	26
Age (<25 years old)	100	134 ±15.5	76.4 ±11.4	95.6 ±10.3	93.5 ±26.7	62.6 ±57.4	96.7 ±0.9	25

Table 7. Test of Means.

Dependent Variable	Mean Value at Elapsed Time (Minutes)				P-Value
	0	***10***	***20***	***30***	
Systolic Pressure	127.7	140.6	131.7	140.2	0.4228
Diastolic Pressure	74.8	76.4	74.5	81.3	0.2782
Heart Rate	71.2	88.8	97.1	102.5	0.0352
TEWL	10.0	54.8	95.3	115.2	0.013
Tympanic Temperature	97.9	98.7	99.1	99.2	0.0577
WBGT	25	26	26	26	0.2254

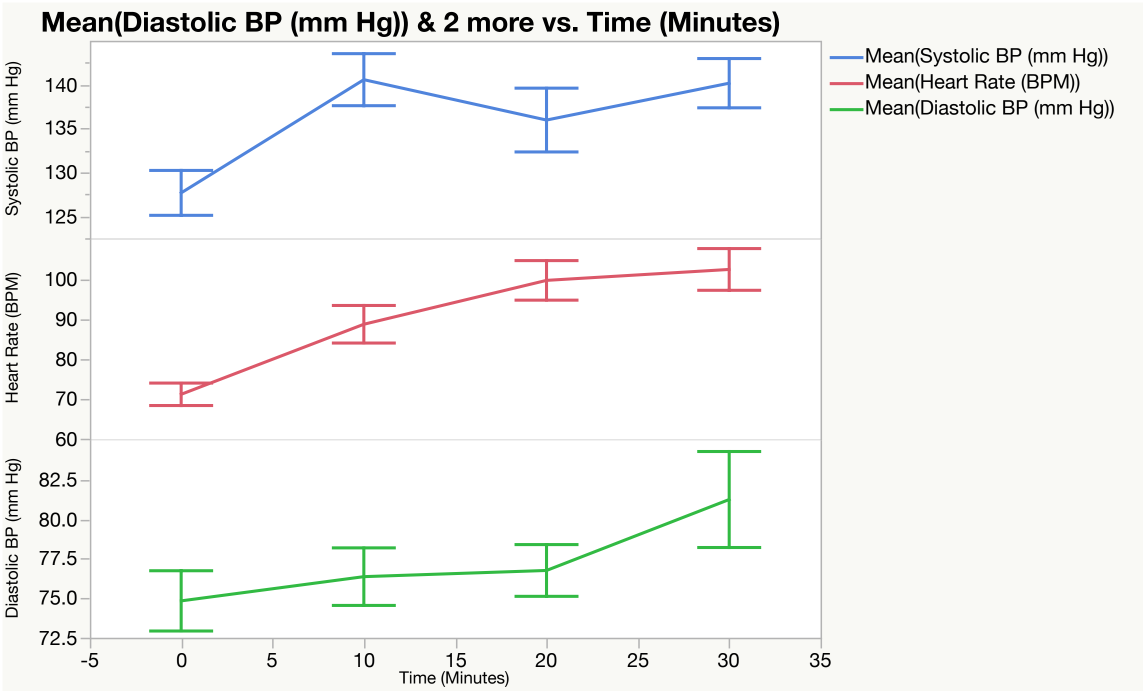

Figure 5. Systolic Blood Pressure, Heart Rate, and Diastolic Blood Pressure Means Over Time.

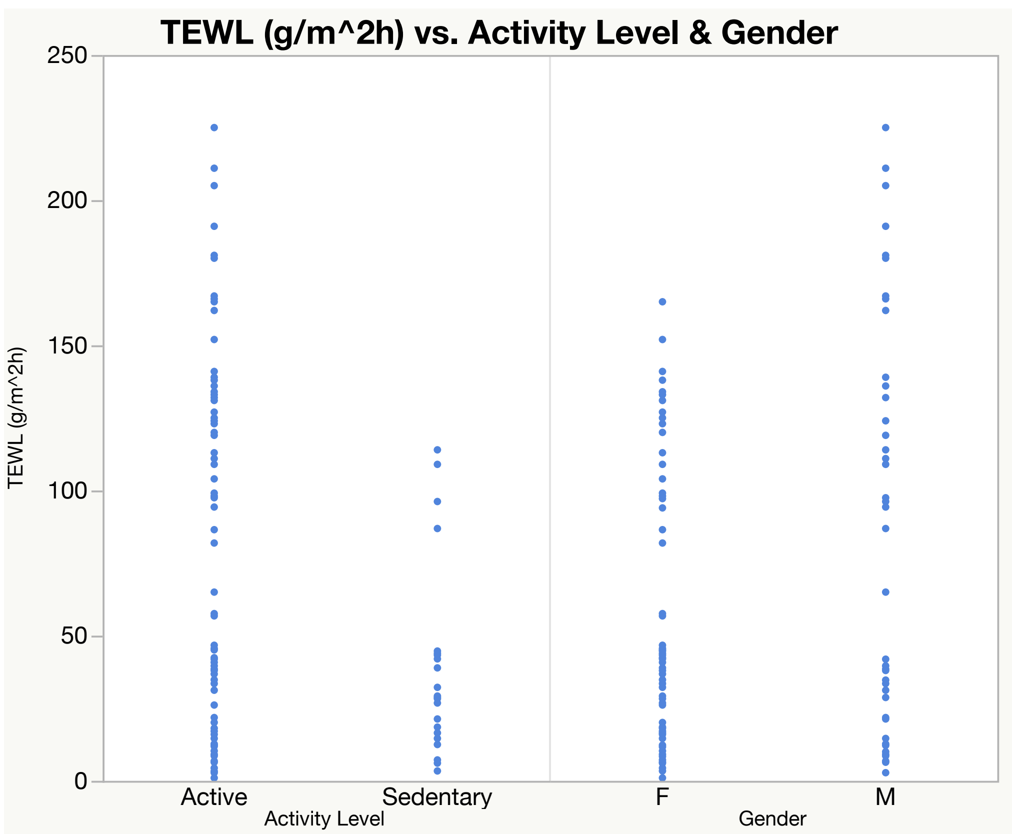

Figure 6. Transepidermal Water Loss (TEWL) vs. Activity and Gender.

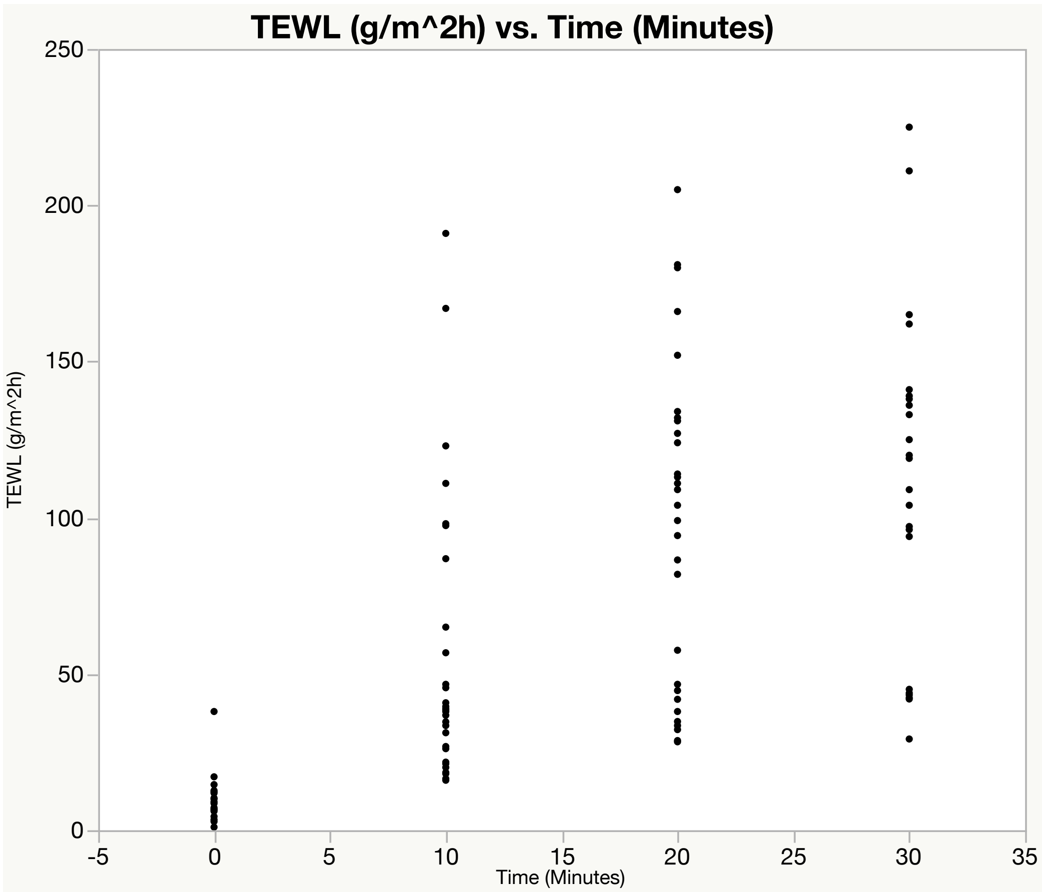

Figure 7. Transepidermal Water Loss (TEWL) vs. Time.

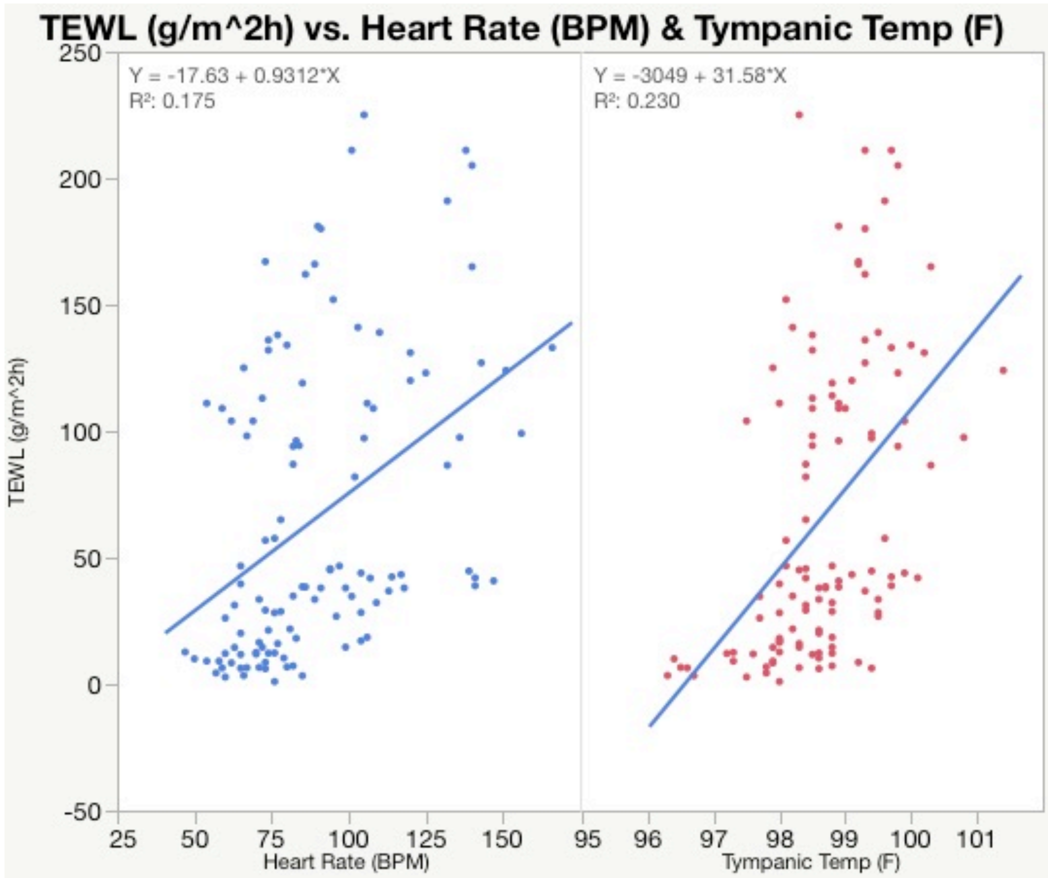

Figure 8. Transepidermal Water Loss (TEWL) vs. Heart Rate and Tympanic Temperature.

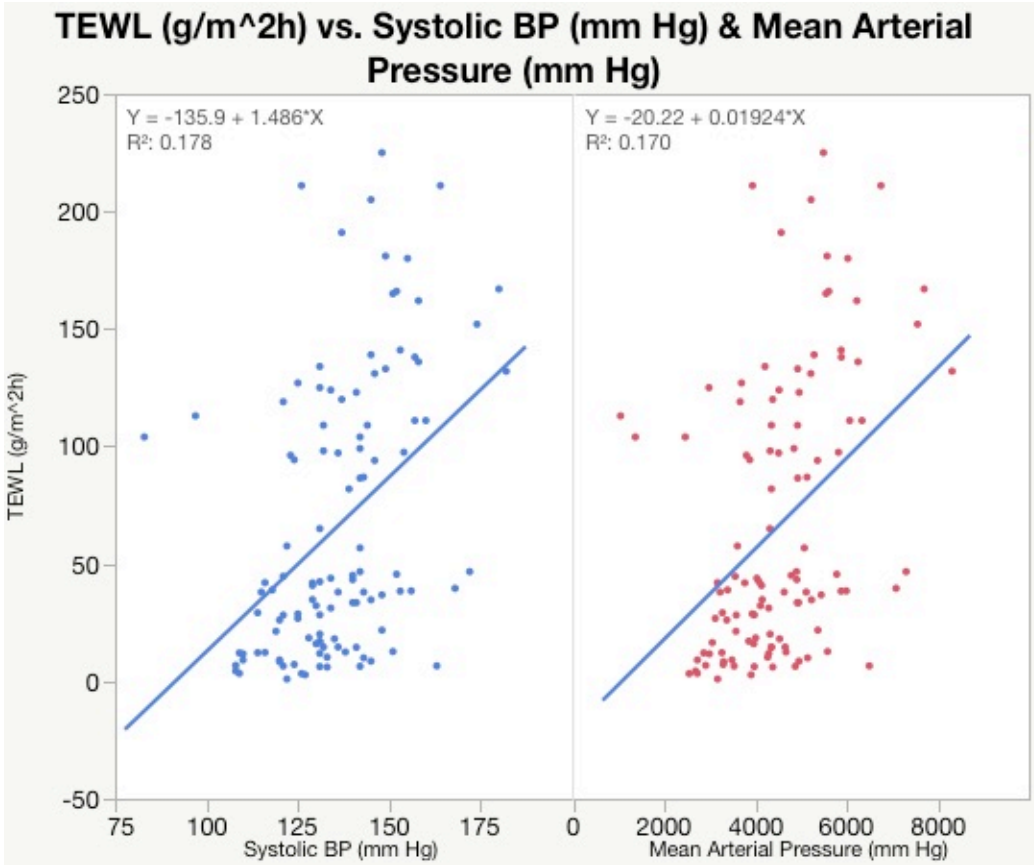

Figure 9. Transepidermal Water Loss (TEWL) vs. Systolic Blood Pressure and MAP.

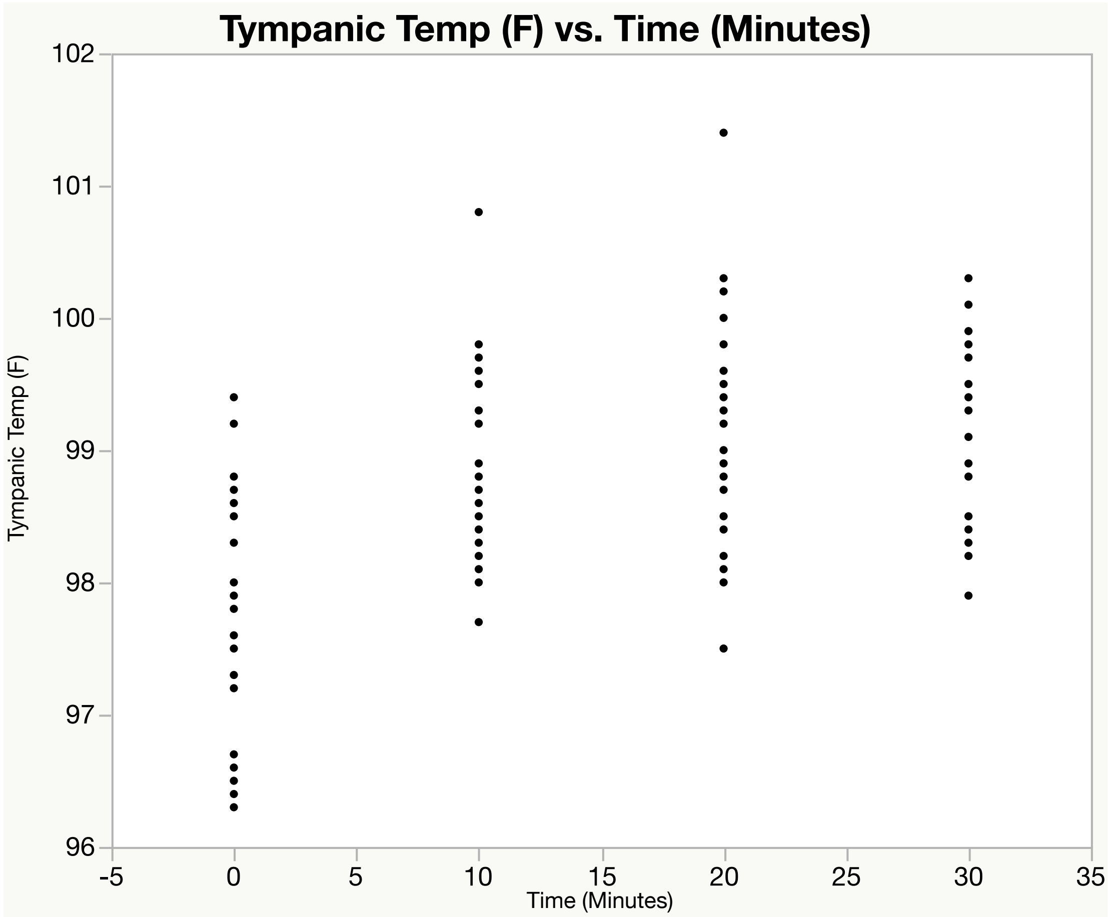

Figure 10. Tympanic Temperature vs. Time.

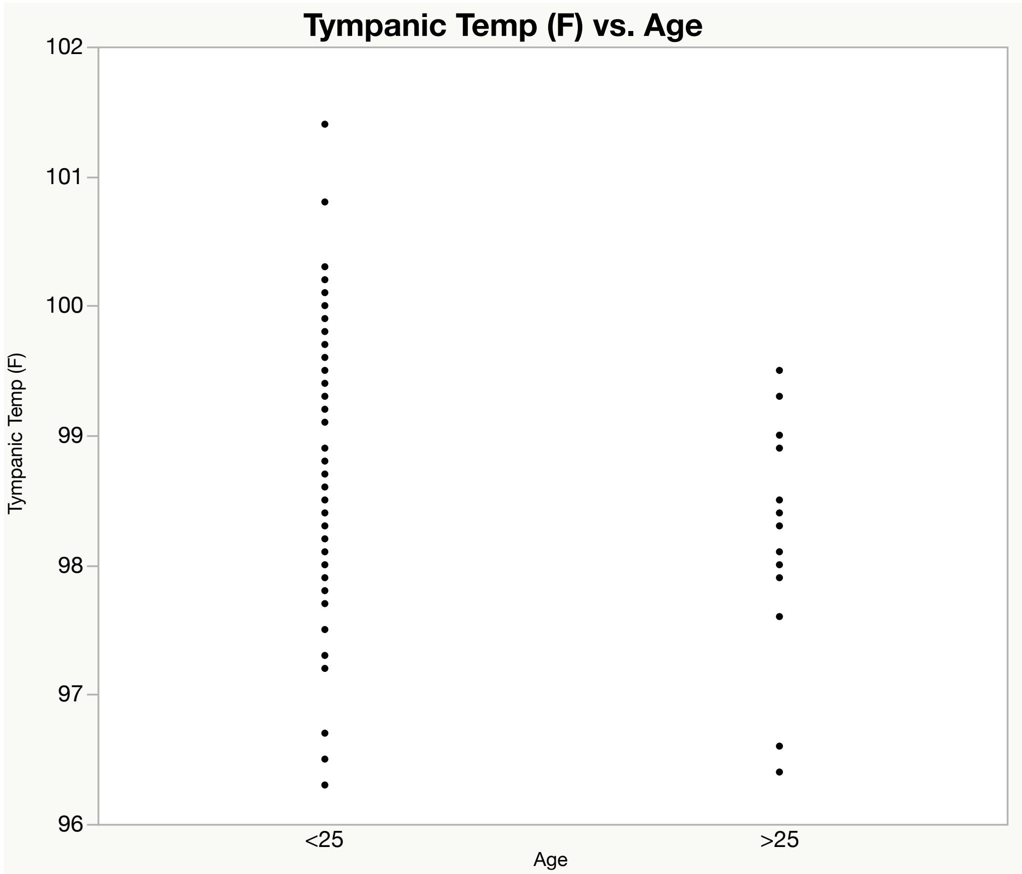

Figure 11. Tympanic Temperature vs. Age.

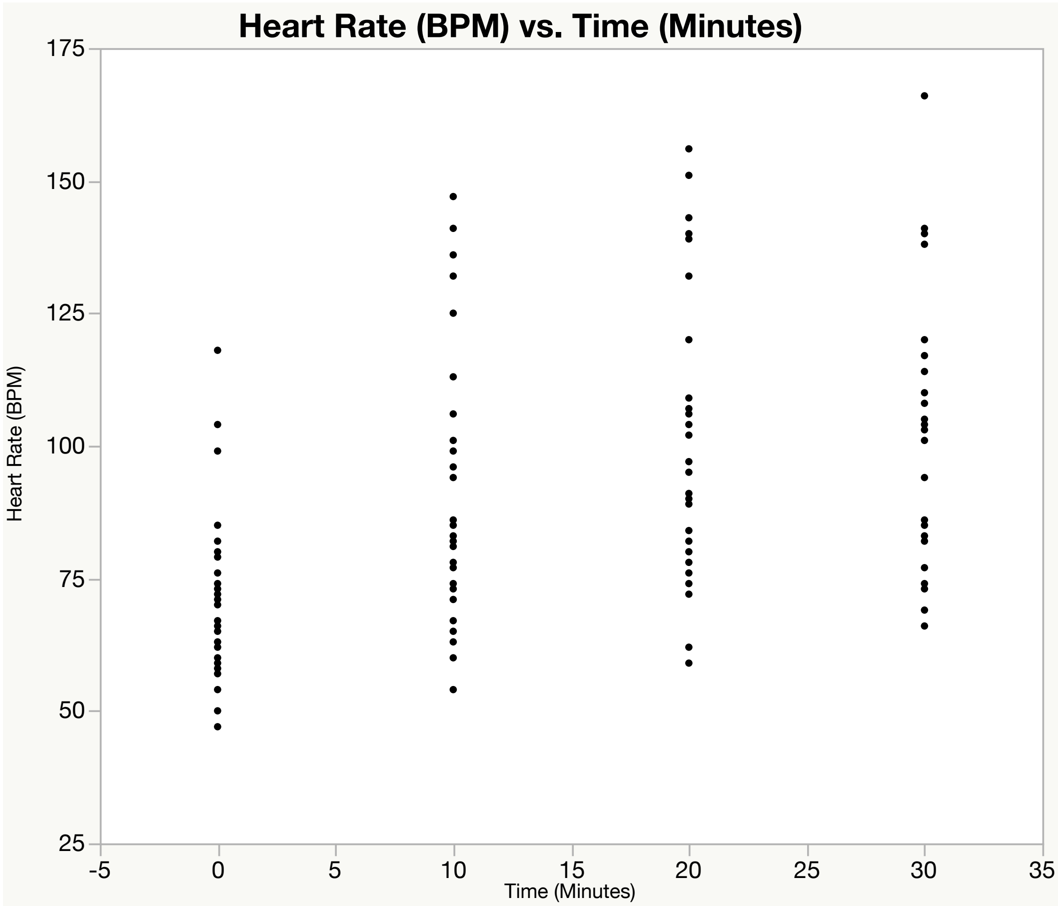

Figure 12. Heart Rate vs. Time.

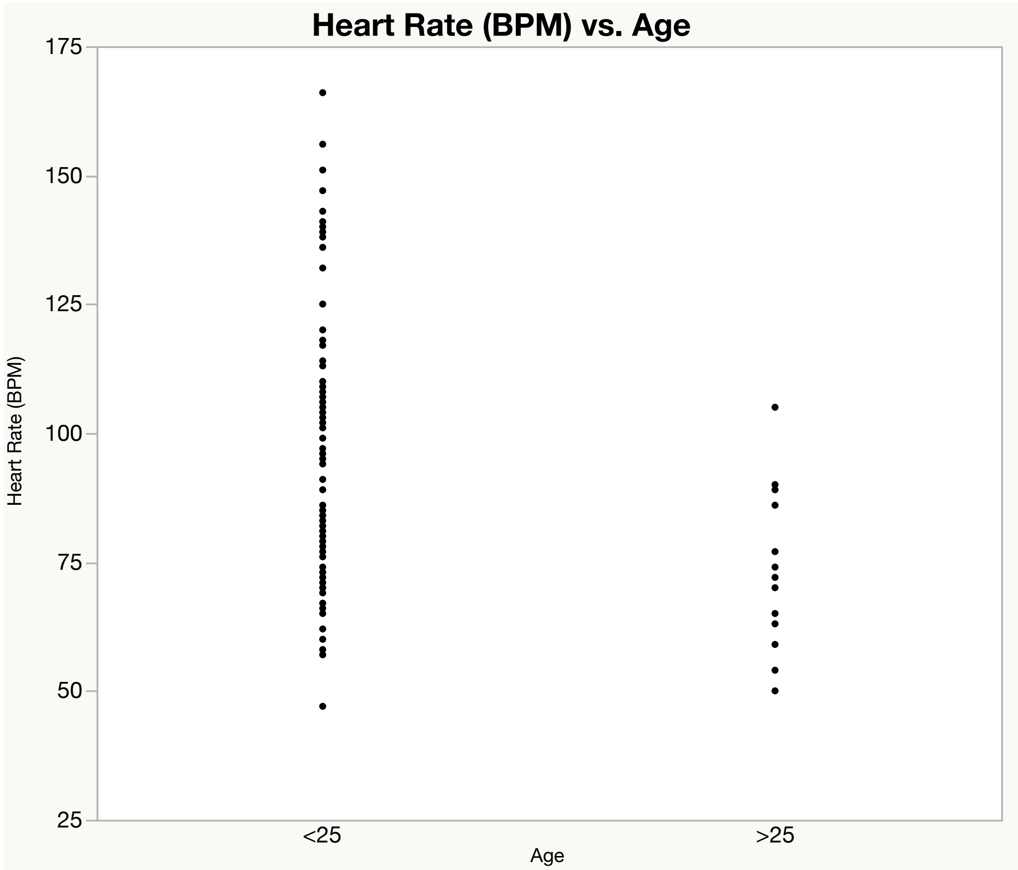

Figure 13. Heart Rate vs. Age.

Chapter 6
DISCUSSION

The primary objective of this study was to determine how physiological metrics, including TEWL, core body temperature, heart rate, and blood pressure, per individual characteristics, including gender, age, and self-expressed activity level, change over time while exposed to a high heat risk environment.

It has been found by previous researchers, as listed in *Chapter 3: Background*, that in a high heat risk environment, that time has a significant effect on diastolic pressure and heart rate ($P<0.05$). Figure 5 shows how heart rate and diastolic pressure change over time, which are statistically significant relationships. It has also been found in previous research that diastolic pressure, systolic pressure, and heart rate mean changes over time are known to have a maximum reached after 20 minutes of exercise in a high heat risk environment. These results in conjunction with this finding are also depicted in Figure 5. The resulting maximums of systolic blood pressure, heart rate, and diastolic blood pressure were observed at 10 minutes, 30 minutes, and 30 minutes, respectively—which is in stark contrast to at 20 minutes as previously discovered. The difference in the time of maximum values of these factors may be due to limitations as described in the next chapter, which include the inadequacies of the environmental chamber used, uncontrollable fluctuations in chamber temperature and humidity, as well as taking measurements outside of the environmental chamber. TEWL and heart rate have a statistically significant correlation ($P<0.05$) as found by Whitt *et al*. in 2008. Activity level was not a significant factor for TEWL, which was found to have a significant effect by Whitt *et al*. The small sample size of subjects over 25 years old (n=5) compared to subjects younger than 25 years old (n=25) could be one explanation for the difference in findings between these two studies.

Tympanic temperature was added as an additional factor to attempt to further explain the thermoregulation process and changes to the body leading up to a heat stress related event. Tympanic temperature serves as an estimate of body core temperature in this study to reveal a

relationship, if any, to the other physiological and cardiovascular metrics, as well as to find a relationship over time, in a heat stress environment. Figures 10-11 show the significant findings discovered in this study related to tympanic temperature. As mentioned previously, tympanic temperature has a significant effect on time exposed to high heat and humidity, heart rate, TEWL, and age. Tympanic temperature (or core body temperature), as expected, increased over time with increasing exposure to high heat and humidity. As the body produces excess heat, the body's core increases, which can be fatal if the body is not able to get rid of that heat and cool the body (like by sweating). This thermoregulation reaction explains why TEWL increases over time for the same reason—to cool the body as the core warms—shown in Figure 7. This study, as displayed in Figure 10, shows that core body temperature is higher for younger people than those older than 25 years old. This contradicts the study done by Anderson *et al*. in 1985, where physiological responses of eight older postmenopausal and eight younger women with similar subject characteristics were compared during moderate intensity exercise at 25ºC wet bulb (Anderson, 1985). Anderson's study resulted in mean body temperature (via rectal thermometer) increasing by 1.36ºC for the older women and only 0.86ºC for the younger women after 90 minutes of exercise. Compared to the Anderson study, a tympanic thermometer was used instead of a rectal thermometer, and the number of older subjects was minimal compared to the younger subjects recruited for the study, which are two possible explanations for these differing relationships.

TEWL was found to be greater on average for active versus sedentary subjects. Active individuals tend to sweat more at the beginning of an exercise routine, which may have led a higher average sweat rate for active subjects since the exercise protocol lasted for only 30 minutes. The sweat onset times of long distance runners and sedentary subjects were determined to be significantly shorter for the runners in a study done in 2014 (Lee, 2014). If the exercise activity was longer, a similar TEWL average between the active and sedentary individuals might be revealed. In this study, TEWL was found to be higher for younger subjects than those over 25 years old, which could be explained by the argument that younger people tend

to be more active. TEWL and gender had a significant correlation, with females having on average lower TEWL than males.

Sweat rate and MAP as well as sweat rate and systolic blood pressure were shown to have a positive correlation in this study. Typically systolic blood pressure increases with age as large arteries become stiffer and as risk of cardiac and vascular diseases increases. As the arteries become stiffer, their elasticity decreases and therefore their ability to expand when large amounts of blood flow through them is compromised. When looking at the mean of diastolic blood pressure and the mean of systolic blood pressure, both stayed relatively constant over time ($P>0.05$). Because the systolic blood pressure was relatively higher than normal (120 mm Hg) after the "time 0" measurement and the diastolic reading stayed in the normal range (80 mm Hg), this pattern could lead to an indication of isolated systolic hypertension, the most common form of hypertension (Harvard, 2009). This condition is common in older adults and increases risk of heart failure.

Heart rate is known to be higher when a subject undergoes heat stress than when not undergoing heat stress at any given systolic pressure (Whitt, 2008a). Naturally, heart rate increased over time to compensate for the increasing oxygen demand in the high heat risk environment, as shown in Figure 12. Whitt *et al*. also explains that TEWL increases as heart rate increases (see Figure 8) as a result of increased nervous system activity (Whitt, 2008a). The Anderson study also looked at changes in heart rate for the elderly and young women during exercise, and there was no significant difference found (Anderson, 1985). Our study showed a significant relationship between heart rate and age (Figure 13). Heart rate was found to be higher for those younger than 25 years old, which could have a few different explanations—one being because of the small sample size of subjects over 25 years old, and another being that older individuals do not have the capacity to reach the same maximum achievable heart rate as younger people (see Equation 4).

Chapter 7

SUMMARY AND CONCLUSION

7.1 Contributions to the Field

The study resulted in the combination of several measurements of various physiological factors, whereas previous similar studies tend to focus on only one or a few points of measurement. Because multiple physiological measurements were included in one study, possible relationships between the measurements were easier to identify with the same controls and subject characteristics.

Currently there are no specific Occupational Safety and Health Administration (OSHA) standards for occupational heat exposure. Although the Centers for Disease Control and Prevention (CDC) has published in collaboration with OSHA and the National Institute for Occupational Safety and Health (NIOSH) about occupational exposure to heat and hot environments, the CDC has made recommendations to minimize worker health risk, however, with no concrete standards. The results from this study could aid in the continuance of the discussion on how to determine appropriate threshold limit values more accurately corresponding to an individual worker. The recommended heat stress alert and exposure limit (RAL and REL) equations for healthy unacclimatized and acclimatized workers, respectively, NIOSH uses to represent the heat stress limits of a “standard man” of 70 kg (154 lbs) body weight are displayed below, where M represents metabolic rate in Watts (W) (Jacklitsch, 2016):

$$RAL\ [°\mathrm{C} - WBGT] = 59.9 - 14.1 \log_{10}(M)\ [W] \quad (7)$$

$$REL\ [°\mathrm{C} - WBGT] = 56.7 - 11.5 \log_{10}(M)\ [W] \quad (8)$$

NIOSH claims these limit equations are supposed to be representative of female workers as well as healthy (i.e., medically and physically fit) workers (Jacklitsch, 2016). Gender, age, acclimatization, and many other factors that make individuals unique, as well as their work conditions, work attire, and physical demands must be introduced into this model in order to produce more accurate limit values per worker. To further justify this argument, evidence has found acclimatized workers who work in environmental conditions above the recommended

ceiling limit to not have shown adverse health effects, which proves that there are factors that are not being taken into account when determining these limit value equations (Jacklitsch, 2016). The CDC recognizes that additional research is needed to further understand the effects of heat stress and climate change, and this study and future studies like it can help to determine the standards needed to protect workers' health in terms of heat stress.

Wearable technologies are quickly becoming popular tools for tracking an individual's health, however they are still developing to be more useful. Some suggestions for improvement include updating such technology (i.e., FitBit™) to add alarms and continuously track blood pressure, TEWL, and heart rate. A pattern of high systolic blood pressure is one example of a measurement that could be tracked in wearable devices that could alert the user of increased risk of heart failure and let doctors know of their condition for future treatment.

7.2 Limitations

There are some limitations that apply to this study. The Vapometer™ that measured TEWL was read outside of the environmental chamber, immediately after the subject left the high-risk environment. This limitation cannot be improved upon because the Vapometer™ must be used outside of an environmental chamber because the chamber environment can influence the Vapometer™'s microenvironment. Having a similar device that measures sweat rate in an environmental chamber would be a great tool to measure sweat rate more accurately and efficiently, but such technology is limited. The measured blood pressure, heart rate, and tympanic temperature were also measured immediately after stepping out of the environmental chamber. The use of wearable devices, like a FitBit™ and other wrist health monitoring technologies, could help to increase the number of data points collected over time, and thus providing a more reliable dataset to draw conclusions from.

The most obvious limitation in this study involved the using of a make-shift environmental chamber that does not control heat or humidity to the degree of accuracy as a normal environmental chamber would. The environmental chamber used in this study was the only

environmental chamber available on the Cal Poly campus that could fit a human and a step exercise machine. Also, the environmental chamber used in this study has an attached heater unit that is not integrated into the room, so the emitted heat is assumed to not have spread evenly throughout the room. Renting an environmental chamber was researched, but the available funds would not have been able to cover the costs of renting a large enough environmental chamber for the time needed to do the experiment.

The subject's BMI, activity level, and age were answered at the subject's discretion, so there is a possibility the subjects answered untruthfully. This could have led to recruitment of unfit subjects and incorrect sample sizes for activity level and age groups.

7.3 Future Work

Future studies may include recruiting subjects with BMIs higher and lower than the "healthy weight" category to test for an additional individualized, physiological factor. BMI has been thought to be an inaccurate measure of a person's health, especially since it does not take into account gender, age, and muscle mass. BMI is not calculated based on percentage of lean mass versus fat mass, which can lead an athletic person to have a high BMI and may be seen as overweight due to a high percentage of lean mass (Zelman, 2007). Because all of the subjects are within a "healthy weight" category, another study can be completed with a wider range of BMIs to test the impact of BMI on the outputs measured.

Another study could identify results for a type of exercise routine other than using a step-climber machine. For example, upper versus lower body exercises could be included to determine any significant differences in thermal regulatory patterns. As Gisolfi and Wenger mention in "Temperature Regulation During Exercise: Old Concepts, New Ideas," heart rate and arterial blood pressure are much greater when performing arm exercises compared to leg exercises at the same rate of Oxygen uptake (Gisolfi, 1984).

Heat acclimatization, or heat tolerance response from exposure to environmental heat stress, a well-studied factor in heat response, is known to be correlated to sweat rate but was not

included in this study (Jacklitsch, 2016). Heat acclimatization is different per individual depending on factors similar to the ones used in this study, including age and activity. Acclimatization state per individual is possible to classify with a similar test performed in this study.

Furthermore, arterial compliance should be another factor included in a future study. This study was meant to measure arterial compliance along with TEWL, heart rate, MAP, systolic blood pressure, and diastolic blood pressure, but the equipment necessary could not be used.

7.4 Summary and Closing Statement

This study succeeded in adding upon previous researcher's work in further understanding human physiological changes in a high heat risk environment. Environmental metrics, including WBGT and HI, classify dangerous environments for any individual regardless of their unique characteristics (age, sex, medication, health history, BMI, etc.). This generalization is dangerous for those who do not fit in the "general" population category that WBGT and HI specify. An individualized model for those of at least different ages, gender, and activity level should be developed in order to more accurately predict when someone is approaching heat exhaustion, heat stroke, and other heat related illnesses.

With the addition of tympanic temperature as an independent factor, we are now able to predict patterns of core body temperature over time before a heat stress event, as well as with the other independent variables: heart rate and TEWL. The relationships between these factors and certain groups of people regarding age, activity level, and gender have individualized the apparent patterns leading up to a heat stress event that can better predict on an individual basis. Future experiments should continue to study individual physiological changes in controlled high heat and humidity environments to more accurately determine the accuracy of the patterns found in this study.

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Appendix

APPENDIX A: INFORMED CONSENT FORM

INFORMED CONSENT TO PARTICIPATE IN A RESEARCH PROJECT, "Predicting Heat Stress Event with Physiological and Environmental Metric-Based Mathematical Model"

A research project on heat stress is being conducted by Dr. Michael Whitt and McKenzie Barlow in the Department of Biomedical Engineering at Cal Poly, San Luis Obispo. The purpose of the study is to measure WBGT, TEWL, arterial compliance, blood pressure, and heart rate of human subjects in a controlled temperature and humidity environment while exercising. The measurements will be used to find a relationship between individual metrics and body core temperature as the temperature and humidity in an environment change. The relationship would be used to create an algorithm and mathematical model to predict heat related events before they occur based on an individual's response to exposure of heat and humidity. The model could be incorporated into biomedical devices to mitigate heat stress events that could otherwise be prevented.

You are being asked to take part in this study by exercising on a step climber for up to 30 minutes in a room with controlled temperature and humidity while wearing shorts and a t-shirt. The maximum temperature will be 81.5ºF, and the maximum relative humidity will be approximately 70% corresponding to a WBGT of 27.5ºC. After every 10 minutes of exercise, you will be asked to:

- Expose your left upper arm for a device called a VapoMeter™ to be placed on the skin surface (Measurement of TEWL takes place between 7 and 16 seconds).
- Expose your right arm to use a Cordex Smartcuff™ comprised of a blood pressure cuff and fingertip pulse oximeter, to measure blood pressure under normal conditions and under hyperemia conditions (meaning the CCP is held at 200 mm Hg for five minutes prior to releasing the cuff pressure).

- Expose your right arm to use a CCP with a pulse oximeter on your middle or index finger on your right hand to test arterial compliance.

Your participation will take approximately 45 minutes, allowing for a few minutes for taking measurements during exercise breaks. Please be aware that you are not required to participate in this research and you may discontinue your participation at any time without penalty.

The possible risks associated with participation in this study would most likely be caused by overexertion. However, the safety mechanisms in place to prevent this from happening include screening in addition to self-observation and observation by all key personnel and investigators during testing. If you should experience discomfort, dizziness, exhaustion, or strained muscles, please be aware that you may contact the Cal Poly Health Center at (805) 756-1211 for assistance.

Your confidentiality will be protected. Personal subject information will only exist in two places and contain the following information:

- Your printed name and signature on the signed consent form. (Note: The only people with access to this information prior to sending it to IRB will be the PI, co-Investigators and Key Personnel.)
- The ‘subject contact page’ containing your name, age, gender, phone, and e-mail (Note: The only people with access to this information prior to sending it to IRB will be the PI, co-Investigators and Key Personnel).

There is no direct benefit to you for being involved in this research. However after being involved in this research, you will have a greater understanding of the conditions and mechanisms that increase susceptibility to heat exhaustion. This knowledge may decrease your future probability of suffering from heat exhaustion.

If you have questions regarding this study or would like to be informed of the results when the study is completed, please feel free to contact McKenzie Barlow at mlbarlow@calpoly.edu or (530) 400-9416. If you have concerns regarding the manner in which the study is conducted, you

may contact Dr. Michael Black, Chair of the Cal Poly Institutional Review Board, at (805) 756-2894, mblack@calpoly.edu, or Ms. Debbie Hart, Compliance Officer, at (805) 756-1508, dahart@calpoly.edu.

If you agree to voluntarily participate in this research project as described, please indicate your agreement by signing below. Please keep one copy of this form for your reference, and thank you for your participation in this research.

____________________________________ ________________

Signature of Volunteer Date

____________________________________ ________________

Signature of Researcher Date