

University of Montana

ScholarWorks at University of Montana

Graduate Student Theses, Dissertations, &
Professional Papers

Graduate School

2013

THE ABILITY OF A NOVEL PHYSIOLOGICAL STRAIN SCALE TO PREDICT HEAT STRAIN RISK IN FIELD SETTINGS USING NON-INVASIVE MEASURES OF HEART RATE AND SKIN TEMPERATURE

Jeremy Curtis Basler
The University of Montana

Follow this and additional works at: <https://scholarworks.umt.edu/etd>

Let us know how access to this document benefits you.

Recommended Citation

Basler, Jeremy Curtis, "THE ABILITY OF A NOVEL PHYSIOLOGICAL STRAIN SCALE TO PREDICT HEAT STRAIN RISK IN FIELD SETTINGS USING NON-INVASIVE MEASURES OF HEART RATE AND SKIN TEMPERATURE" (2013). *Graduate Student Theses, Dissertations, & Professional Papers*. 10626.
<https://scholarworks.umt.edu/etd/10626>

This Thesis is brought to you for free and open access by the Graduate School at ScholarWorks at University of Montana. It has been accepted for inclusion in Graduate Student Theses, Dissertations, & Professional Papers by an authorized administrator of ScholarWorks at University of Montana. For more information, please contact scholarworks@mso.umt.edu.

THE ABILITY OF A NOVEL PHYSIOLOGICAL STRAIN SCALE TO PREDICT HEAT
STRAIN RISK IN FIELD SETTINGS USING NON-INVASIVE MEASURES OF HEART
RATE AND SKIN TEMPERATURE

By

JEREMY CURTIS BASLER

B.S. Montana Tech of the University of Montana, Butte, MT, 2011

Thesis

presented in partial fulfillment of the requirements
or the degree of

Master of Science
in Health and Human Performance, Exercise Science Option.

The University of Montana

Missoula, MT

May, 2013

Approved by:

Sandy Ross, Dean of The Graduate School

Graduate School

Dr. Brent Ruby

Health and Human Performance

Dr. Charles Palmer

Health and Human Performance

Dr. John Bardsley

Mathematics

Table of Contents

Chapter 1

Abstract	Page 4
Introduction	Page 5
Statement of Problem	Page 7
Statement of Purpose	Page 8
Hypothesis	Page 8
Significance and Rationale	Page 9
Limitations	Page 9
Delimitations	Page 10
Definition of Terms	Page 10

Chapter 2-Review Of Literature

Heat Stress, Heat Strain and PSI	Page 12
Thermoregulation and the important of T_{core}	Page 14
Core Temperature Measurements and Telemetric Monitoring Systems	Page 15
T_{skin} relation to T_{core} in the heat	Page 17

Chapter 3- Methodology

Experimental Protocol	Page 20
-----------------------	---------

WLFF

Subjects	Page 20
----------	---------

Physiological Monitoring	Page 21
Weather	Page 21
<u>Mount Evans Ride</u>	
Subjects	Page 21
Physiological Monitoring	Page 22
Weather	Page 23
Calculations of PSI and PSS (Both)	Page 23
Statistical Analysis (Both)	Page 24
<u>Chapter 4- Results</u>	
WLFF	Page 26
Mount Evans Ride	Page 31
<u>Chapter 5- Discussion</u>	
WLFF	Page 38
Mount Evans Ride	Page 40
Conclusion	Page 41
References	Page 42

Abstract

There are many occupational and professional careers that demand performance at the highest levels of function possible in hot environments. During heat exposure, the body undergoes a battery of physiological changes in response high heat stress. A problem arises when current physiological strain models are applied towards instantaneous monitoring of physiological strain in field settings. The Montana Center for Work Physiology and Exercise Metabolism has developed a novel equation to assess physiological strain, coined the Physiological Strain Scale (PSS), using the metrics of skin temperature (chest) and heart rate. This purpose of this study was to validate the new equations through previously collected data from 2 field studies (N=29, N=12), which varied in workload (Firefighting duties vs. Controlled Wattage Ride), intensity, and environmental conditions (WLFF: $27.4\text{ }^{\circ}\text{C} \pm 3.61\text{ }^{\circ}\text{C}$ and $6.5\text{ mph} \pm 3.0\text{ mph}$ vs. Cycling: $12.5\text{ }^{\circ}\text{C} \pm 7.1\text{ }^{\circ}\text{C}$ and $6.2\text{ mph} \pm 5.7\text{ mph}$). Core temperature, skin temperature (chest), and heart rate were continuously monitored in both studies. Accuracy was assessed between the gold standard PSI and the novel PSS equation by a 2 x 5 ANOVA between the number of overall minutes spent in the following groupings: No/Little= <2, Low=2.1-4, Moderate= 4.1-6, High= 6.1-8, Very high= >8. The novel equation of PSS demonstrated accuracy and reliability in the higher ambient temperature, lower wind speed environment when compared to PSI. However, PSS measured physiological strain to be significantly less in the lower temperature, higher wind speed environment when compared to PSI. This data suggests PSS is reliable in environments with a low $T_{\text{core}}-T_{\text{skin}}$ gradient, but may need adjustment in environments with a large $T_{\text{core}}-T_{\text{skin}}$ gradient.

Chapter One: Introduction

Introduction

There are many occupational and professional careers that require performance of job tasks in hot environments. During exposure, the body undergoes a battery of physiological changes in response to high heat stress. Two markers of these physiological changes are an increase in core temperature and an increase in heart rate. This exposure leads to both heat stress and heat strain. The type of exercise, the environmental conditions, and/or the clothing/uniforms that are required define heat stress. Individually, or collectively, these factors can contribute to the overall development of heat stress. Heat strain is thus manifested when the body is no longer able to maintain a thermoregulatory environment due to the conditions of heat stress. This exposure to heat strain may result in cardiovascular strain, central nervous system dysfunction, volitional fatigue, hyperthermia, heat exhaustion, heat stroke, or even possible death.

Occupational and military personnel that are required to wear protective clothing while engaged in rigorous physical activity require special consideration when subjected to high heat environments. In 2010 alone, the US Army reported 1,734 cases of heat injury, with 207 cases of heat stroke and one death (31). Heat strain has also been suggested as one of the possible factors in sudden cardiac death in firefighters, where the cardiovascular system is overstressed by the demand to keep up with competing needs of thermoregulation and metabolic requirements of the job task (29). Hot working conditions are also common in seasonal construction work, factory and assembly work, agricultural work, and underground mining. Many of the occupations that are subjected to high heat stress are also subjected to long work shifts (12+ hours) that occur during the heat of the day. Due to the increasing demands for productivity in each respective occupational setting, workers are asked to perform at a high intensity, with minimal recovery time. Problems arise when proper attention is not given to controlling heat stress and heat illnesses within these occupational settings.

A number of heat stress/strain models have been proposed for use in both laboratory and field settings. Belding (1) identified that core temperature and heart rate were the two primary determinants of the physiological strain associated with heat stress. Some proposed models included such variables as heart rate, core and skin temperatures, and sweat rate with equal weighting (25). The National Institute for Occupational Safety and Health (NIOSH) even suggests that the monitoring of core body temperature, skin temperature, ear temperature, sweat rate, heart rate, and gross motor activity may be appropriate to indicate heat strain (17). These metrics were later simplified by a cumulative heat strain index which comprised core temperature and heart rate for the evaluation of heat tolerance tests (26). Moran then created the Physiological Strain index (PSI) based upon these two metrics, allowing for the instantaneous assessment of overall physiological strain.

A problem exists when the physiological strain model is applied towards instantaneous monitoring of PSI in field settings. Core temperature is only able to be monitored through three universally accepted methods, including a rectal probe inserted 10 cm past the anal sphincter, esophageal probe measurement, or through the ingestion of an approved, wireless-temperature sensor capsule. Each of these methods provides limitations to practical considerations for data collection outside of the laboratory. The application of a rectal/esophageal probe in field settings or during free-range occupational/military tasks is not feasible. Ingestible thermistor capsules also seem to present similar problems. Their accuracy is most valid when passed through the stomach and into the intestine, where it cannot be altered by the ingestion of liquids (30). In a recent technical report, it was shown that 12.5% subject days were lost due to faulty pills (6). In addition to failure, many subject's data displayed periodic, but rapid, dips in core temperature of 1 or more degrees below a previously stabilized temperature (4, 5). Therefore, the cost and questionable reliability of core temperature pills dampens the efficacy of the PSI model in

arduous field settings, therefore limiting access to the gold standard model for assessing heat stress in occupational settings.

To alleviate the need for obtaining core temperature in the field to instantaneously predict PSI, Buller et al. (3) have proposed a logistical regression to classify subjects as “at risk” or “not at risk” based on a predicted PSI threshold of 7.5. They utilized non-invasive measurements of skin temperature and heart rate to bypass the need for core temperature data. This model was able to predict heat risk status with only a 10% error rate with only one false negative. Comparatively, an earlier classification model had an error rate of 21% (33). This classification model gives us insight into the efficacy of a model utilizing skin temperature, which is much more practical to the application of modern warfighters, firefighters, and other arduous occupational settings.

The Montana Center for Work Physiology and Exercise Metabolism (WPEM) has formulated two novel equations for predicting physiological strain. These two equations are based upon the proven logistical regression model by Buller et al. The new equations, coined Physiological Strain Scale (PSS), predict physiological strain based upon the measurements of skin temperature and heart rate.

Problem

Although a classification model does currently exist, it has only been validated during controlled lab data collection. The majority of the past research to evaluate the efficacy of PSI has been done during controlled lab testing, without a varying ambient temperature or workload. Therefore, it is unclear how the proposed classification models can predict risk status in occupational field settings, across dynamic heat stress levels and changing work loads. Furthermore, it is unknown if “critical temperatures” exist, in which adjustments to the model would aid in decreasing the classification error rate.

Purpose

The purpose of this study was to determine if the novel equation (Physiological Strain Scale) developed by the Montana Center for Work Physiology and Exercise Metabolism (WPEM) match the predictability of the gold standard model of physiological strain (Physiological Strain Index) in a field setting. The field setting data consisted of two previously conducted studies from the summer of 2012. The first, labeled “WLFF”, contained participants who were hotshot firefighters on the High Park Fire in Fort Collins, Colorado. The second field study, labeled “Mount Evans Ride (MER)”, contained participants who cycled up Mount Evans at a controlled work output.

Hypothesis

The hypothesis for this study was that the novel equation (PSS) developed by WPEM predicted physiological strain with the same accuracy as determined by the number of minutes spent in a given strain category (No/Little= <2, Low=2.0-4, Moderate= 4.0-6, High= 6.0-8, Very high= >8) as the gold standard model of physiological strain (PSI) in field settings.

Null Hypotheses

- 1) There will be no significant difference in estimated PSS (established from the measures of HR and skin temperature) when compared to the gold standard measure of PSI (established from HR and core temperature) when classifying persons “at risk” or “not at risk” based on the criteria of a PSI of >7.5.
- 2) There will be no significant difference in the number of minutes spent in each classification zone (No/Little= <2, Low=2.0-4, Moderate= 4.0-6, High= 6.0-8, Very high= >8) between an estimated PSS (established from the measures of HR and skin

temperature) when compared to the gold standard measure of PSI (established from HR and core temperature).

Significance and Rationale

The findings of this research have implications on a more efficient and less invasive way of monitoring a diverse population of persons who are subjected to arduous work in hot conditions, which alters physiological strain. Since the PSS model was shown to accurately predict heat related illness risk in high heat environments, then further research can be done to advance the model into an active monitoring system that can be placed on the person allowing for real-time evaluation and feedback.

Limitations

- 1) The outside environment for each data set was not within our control. There is large variability from day to day, as well from data set to data set. Fluctuations in ambient temperatures can greatly affect core temperature readings.
- 2) In one data set, the workload, work rate, and intensity were self-selected as a part of the participant's occupation. This differs from the second data set, in which the workload was controlled in an attempt to normalize intensity across the subject group.
- 3) The use of any instrumentation can cause error, which is present in each data set. Due to a multitude of errors, there are gaps in all of the vital variables in our data set. A standard procedure will be implemented for the correction of these data gaps.
- 4) Subjects were not random samples; they were a convenience sample.

Delimitations

- 1) All participants in this study are recreationally active or active due to the nature of their profession. Females were included in this study, despite the effects of their menstrual cycles on core temperatures.
- 2) Participants from the wildland firefighting study worked at a self-selected workload, based on their fitness level, job demands and job tasks.
- 3) Participants (Cyclists) from the Mount Evans study will be worked at a controlled work output determined by their max power output during a $VO_{2\max}$ test. Their prescribed workload for the study was set at 50% of their max power output demonstrated on the $VO_{2\max}$ test.
- 4) Participants were apparently healthy and be excluded from the study if they are currently taking any prescription drugs.

Definition of terms

Heat Stress: A level of perceived discomfort that is defined by the exercise load, the environmental conditions, and the type of clothing being worn.

Heat Strain: The physiological consequence when subjected to heat stress, usually defined through changes in core temperature or heart rate.

Physiological Strain Index (PSI): a relatively non-invasive model that calculates the physiological strain on the cardiovascular and thermoregulatory systems based on two physiological parameters, heart rate and rectal temperature.

Physiological Strain Scale (PSS): a proposed non-invasive model that calculates the physiological strain on the cardiovascular and thermoregulatory systems based on two physiological parameters, heart rate and skin temperature (chest).

Recreationally Active Individuals: Individuals who exercise on a regular basis (2-3 times per week), but do not participate in any form of a structured training protocol.

VO₂max: the maximum amount of oxygen an individual's metabolism can utilize during a graded maximal exercise test.

Power Output: A measurement of the actual amount of energy being created by an athletic motion. It is represented in watts.

Self-selected workload: A self-selected workload is defined when the participant selects the intensity and duration of the task at hand. For example, if a firefighter's task at hand was to dig a line, the firefighter would self-select the intensity of which he digs at, how long he digs at that intensity, and how many breaks he gets.

Hotshot Firefighter: A type 1 hand crew firefighter that is specifically trained in wildfire suppression tactics. They have extensive training, high physical fitness standards, and are often in more difficult, dangerous, and stressful assignments.

Chapter Two: Review of Literature

Heat Stress, Heat Strain, and PSI

Firefighters, workers engaged in toxic cleanup, foundry workers, miners, and soldiers are all examples of different groups that are commonly exposed to uncompensable heat stress as a necessary function of their job (11, 13, 19, 26). Uncompensable heat stress exists when the evaporative cooling requirement of the body exceeds the environment's cooling capacity (22). During exposure, these groups are subjected to a battery of physiological changes, with the both heat stress and heat strain. The type of exercise, the environmental conditions, and the clothing/uniform requirements help determine the degree of heat stress. These are the conditional factors that contribute to heat strain, which is the physiological consequence of heat stress. Heat strain is thus manifested when the body is no longer able to maintain adequate thermoregulatory balance due to the conditions of heat stress. This exposure to heat strain may result in cardiovascular strain, central nervous system dysfunction, volitional fatigue, hyperthermia, heat exhaustion, heat stroke, or even possible death. The most dangerous and potentially lethal illness is heat stroke. Recently, the US Department of Defense reported that there were 286 cases of heat stroke and 1854 incident cases of heat exhaustion in 2007 (17, 31). It is also reported that the crude incidence rates of heat stroke and heat exhaustion are 0.21 and 1.36 per 1000 person-years, respectively (17).

In an attempt to gain understanding and control over the threshold at which ill effects of heat stress begin, a search for a strain index began. Many measures of heat strain were proposed, including various combinations of heart rate, core and skin temperatures, and/or their rates of change, and sweat productions. Numerous attempts have been made to combine environmental parameters, such as wet bulb globe temperature, and physiological variables in hopes of developing a unified heat stress index (27). These indices can be generally divided into two

categories: effective temperature scales, which are based on meteorological parameters only, and rational heat scales, which include a combination of environmental and physiological parameters. Multiple indices utilizing effective temperatures scales were proposed, however, they lacked the capability to adjust for different levels of metabolic rate and different clothing microenvironment (27, 30). The best known HSI index was presented by Belding and Hatch, for which the metabolic heat production, heat transfer between the body and the environment, and the evaporative capacity of the environment were related (1, 27). This index is widely used and accepted, yet even according to Belding himself, there are situations in which heat strain was grossly under predicted or over predicted by the model (1, 26, 27). Therefore, the scope was changed to indices that are based on physiological parameters. Most notably, Robinson et al. suggested an index of physiological effects that relied on rectal temperature, heart rate, skin temperature, and sweat rate, which was further changed to include the measurements of only heart rate, rectal temperature and sweat rate and body heat storage by Hall and Plote (1,26). This index failed to provide an instantaneous measurement of strain because of the complexity of its calculations; therefore it was not readily accepted universally, leaving a void for a strain index still unfilled.

In 1998 Moran et al. (26) suggested and validated a simple physiological strain index that is commonly referred to as PSI. He used two database sets in the study, utilizing the first to construct the new index, and the second to validate the developed index. In order to construct the index, he tested 100 healthy young men of different fitness and heat acclimation levels by having them exercise with only shorts and shoes on in a hot and dry environment of 40°C and 40% relative humidity for 120 minutes at a speed of 1.34 m/s and a 2% grade. He gathered heart rate and rectal temperature data at 1-minute intervals. Rectal temperature was recorded by the insertion of a thermistor probe 10 cm past the anal sphincter. Heart rate data was collected utilizing the Polar heart rate belt electrodes. From these data, the PSI scale was assembled,

which enables an objective evaluation of heat stress ranging from 0-10 at any given time using the change in two variables (rectal temperature and heart rate) relative to expected resting values. His validation of this equation showed that there was statistical significance between significantly higher values of T_{rectal} and HR observed in hot-dry climatic conditions. This index has become the gold standard composite score for quantifying heat strain because of its ability to adequately depict the combined strain reflected by the cardiovascular and thermoregulatory systems, as well as its simplicity and ability to predict strain instantaneously. Regardless, the requirement for sophisticated monitoring equipment minimizes the practicality of obtaining these measures during most occupational settings.

Thermoregulation and the importance of T_{core}

Proper function of the human body is dependent on maintaining homeostasis, most notably, thermoregulatory homeostasis. This occurs at a core temperature (T_c) between 36.5°C to 38.5°C (14, 25). The greater the deviation from normal thermoregulatory homeostasis, the greater the malfunction that occurs in the body. A T_c above 41.5°C or below 33.5°C causes a fast decline in the proper functioning of the body, which could result in injury and eventually death (23). There are two ways core temperature can become deviated from the normal range. The first is due to fever resulting from infection to an internal system of the body, which the body responds to by increasing core temperature. The second mechanism is the disturbance of the thermoregulatory homeostasis due to an upset of the balance between the amount of heat absorbed from the environment, metabolic heat production and the amount of heat emitted from the body. Manifestations of erratic changes in core temperature can lead to hypo or hyperthermia, a decrease in performance, heat exhaustion, heat stress, heat strain, heat stroke, and possibly death (4, 12, 16, 24, 25).

Core Temperature Measurements and Telemetric Monitoring Systems

In humans, the temperature of blood in the pulmonary artery (PA) is considered “true” core body temperature (21). Temperature measurements from an esophageal site at the level of the heart have been shown to correlate with PA readings; therefore it is one of the accepted practices in laboratory settings (21). Typically, the measurement of core temperature in research settings is done through the invasive practice of inserting a temperature sensitive probe 10 cm past the anal sphincter or through the nasal cavity and down into the esophagus. Both methods are not easily administered in occupational field settings, leading researchers to look at telemetric methods to obtain temperature data.

In the 1960's, micro-electric transmitters were used to send and receive signals via radio waves, allowing for the monitoring of variables from afar. Kolka (16) conducted a study to attempt to validate the responsiveness of the three accepted measuring techniques for core temperature, which included esophageal temperature, rectal temperature and ingestible thermistor (pill) temperature. In this study, subjects ingested a CorTemp (St. Petersburg, Fla.) brand temperature sensor and then ate a small breakfast. After a 2 hour (± 0.5 hours) wait, subjects then performed a 40 minute exercise bout at 40% peak VO_2 in a 29.5°C ($\pm 0.6^\circ\text{C}$) environment. Following the bout, they had a 15 minute rest period. Following the rest period, the subjects went through three cycles of intense exercise of 5 minutes at 80% peak VO_2 . This was utilized to test whether or not the system accurately tracked rapid changes in core temperature. The total length of the experiment was 100 minutes. It was shown that esophageal temperature and pill temperature both reached steady state faster ($p < .05$) during moderate exercise than rectal temperature did and during the intense exercise bouts, pill temperature was less responsive than esophageal temperature, but more responsive than rectal temperature, demonstrating the potential usefulness of telemetric measurements.

In 2002, Moran and Mendal (23) set out to review the different existing methods for obtaining T_{core} in order to emphasize the need for a single, noninvasive, and universally used device for obtaining T_c measurement. They concluded that although many developments in the last century, in particular the past two decades, have led to the advancement of telemetry monitoring systems and other non-invasive techniques for obtaining T_{core} , the use of a mercury thermometer under the tongue is still the most widely accepted practice across the world. Although measuring T_{core} via a mercury thermometer under the tongue is acceptable for individuals who are at rest, it is not feasible to monitor core temperature this way in an individual who is working or exercising.

Furthermore, a more recent study (2007) aimed to validate telemetric core temperature measurements even further, utilizing newer technology in the form of tympanic membrane thermometry. Easton (7) compared the accuracy of an ingestible telemetry pill with an infrared tympanic membrane thermometer and a traditional rectal thermistor during exercise induced heat stress. The protocol consisted of subjects completing a 40 minute constant-load exercise at 63% WR_{max} followed by a 16.1 km (10 mile) time trial at ambient temperature of $30 \pm 1^\circ\text{C}$ and a humidity of $70 \pm 3\%$. On each of the four trials, which were separated by 1 week, core temp pills were ingested 8 hours prior to exercise. Subjects were required to consume 2.14 ml cold water (5°C) per kilogram of body mass during the 40 minute trial. In the results, the authors show that the ingestible telemetry pill system does provide valid measurements of T_c during rest and exercise-induced hyperthermia (even up to 39.5°C) when compared to traditional rectal core temperature measurements (T_{re}), it is necessary to ensure the pill has entered the digestive tract fully before the onset of exercise to obtain accurate results due to the effects of ingestion of cold beverage on the temperature of the stomach. They also show that tympanic core temperature (T_{ty}) parallels T_{re} for the first 20 minutes of exercise, however it was significantly lower than T_{re} for the remainder of the exercise period. Therefore, they concluded that T_{ty} is only valid during

rest and at the onset of exercise up to a core temperature of 37.5°C, and is subject to variability due to selective brain cooling.

T_{skin} relation to T_{core} in the heat

Physiological strain has become an increasing concern as it pertains to heat injury. From this concern, many different monitoring techniques and models have come about to try to effectively stratify subjects as being “at risk” or “not at risk” for a heat related illness when it is known that the subjects will be undergoing an intense workload or will be subjected to a harsh environment. Until recently, the most widely accepted monitoring techniques and models have based their predictions on two main variables: heart rate and core temperature. Although the accuracy of predicting heat strain from core temperature is high, the collection of a precise and reliable core temperature measurement has posed a challenge that is difficult and impractical in occupational field settings. The use of modern day technologies to obtain field data in occupational settings has become a very expensive and unreliable practice.

Body temperature changes during exercise reflect the balance between metabolic heat production and exchange with the environment, whether that is uncompensable or not. The heat balance equation describes the relationship between heat production and loss to the environment:

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

Where: S = the rate of body heat storage, M = the rate of metabolic energy production, W= mechanical work, R+C = the rate of radiant and convective energy exchanges, respective, and E= rate of evaporative loss. The sum of all of these variables results in a positive or negative “S” which indicates a gain or loss in heat, respectively. This net loss in heat results in a subsequent net loss in body temperature (14). It has been shown that trained athletes are capable of handling a core temperature greater than 40°C if the proper conditions for adequately dissipating heat exist

(2). The ability to tolerate such a high core body temperature relies on the body's ability to regulate metabolic heat production. This occurs when heat flow is carried by the blood from the core to the skin to be dissipated through evaporative cooling (14). The ability to tolerate higher core temperatures is then closely related to the subject's skin temperature, as a warmer skin temperature creates a greater circulatory strain (14). For this reason, it is suggested that core temperature should not be used as the standard for measurements to estimate real time heat strain, as the dynamic relationship between the environment and the body is not justly represented by core temperature response alone.

In 2008, Buller et al. (3) set out to build a logistical regression model to identify individuals "at risk" for heat strain as determined by the PSI threshold. This model was based on heart rate, skin temperature, and PSI data. The intent was to build a model that produces a classification of risk based upon heart rate and skin temperature alone. Two different sets of data were analyzed, which included exercising individuals (who were with and without Personal Protective Equipment). Personal Protective Equipment (PPE) is defined by OSHA as any equipment worn to minimize exposure to a variety of hazards. Both data sets included the measurements of heart rate, core body temperature, and chest skin temperature. A logistic regression model was assembled using group one's data (n= 8, 40 bouts of exercise), then validated using group two's data (n=41, 41 bouts of exercise), and a final model utilizing input from both groups, validating the combined data set, was developed. The data suggested that the model effectively identified individuals at risk for exceeding a $PSI > 7.5$ with a classification error rate of only 10%, including only one false negative.

In a more recent study, Cuddy et al. (5) evaluated the previously developed index model using heart rate and skin temperatures. There were 56 male participants in his study, all of whom completed two randomized trials within a counterbalanced cross-over design over the span of

two weeks, with a minimum of 7 days between trials. The 90 minute walking trials were completed in an environment of either 43.3°C and 40% humidity or 15.5°C and 40% humidity. The classification for “at risk” or “not at risk” was set based on the PSI threshold of 7.5, as previously identified by Buller et al. (3). The model successfully classified all participants as “not at risk” during the cool trial, and exhibited 4 false positives and 1 false negative during the hot trial at the 40% decision boundary, while only showing 2 false positives and 2 false negatives at the 30% decision boundary. This seems to validate what Buller et al. (3) had previously demonstrated, exhibiting the rationale for the use of skin temperature and heart rate as variables to predict the accepted gold standard PSI marker of heat related illness risk.

Chapter Three: Methodology

Experimental Protocol

The purpose of this study was to evaluate the effectiveness of our novel PSS model by using data collected from two field studies. These data represent actual work activities and conditions that were experienced by wildland firefighters during fire suppression and recreational cyclists during a controlled intensity ride. Data on wildland firefighters (WLFF), specifically hotshot crews, was collected at the High Park Fire in Fort Collins, Colorado. Data on recreational cyclists was collected during an ascension ride up Mount Evans, near Idaho Springs, Colorado.

Each study was reviewed and approved by the University of Montana Institutional Review Board for the Use of Human Subjects in Research. All study volunteers were briefed concerning the study procedures and risks and provided their written consent before participating in the studies. A brief summary of each study is given below.

Wildland Firefighters (WLFF)

The first field study (denoted WLFF) consisted of data collected from 2 different wildland firefighter type 1 crews (hotshots) who were fighting a fire in Fort Collins, CO. The WLFF team members, based on their experience, training and physical fitness, qualify as elite professionals.

Subjects (WLFF)

Subjects for WLFF (N=29) were recruited on site, and volunteers included both male and female firefighters between the ages of 18 and 40. Subjects were instructed on what their obligations would be while being included in the study, successfully completed a physical activity readiness questionnaire (PAR-Q) and signed an institutional review board approved consent form.

Physiological Monitoring (WLFF)

WLFF subjects reported to our site shortly after waking on day 1, before their first meal, to be fitted with the Equivital (Hidalgo Limited, Cambridge, UK) monitoring system and to ingest a VitalSense (Philip Respironics, Bend, OR) core temperature capsule. The use of the Equivital software in medical mode allowed us to confirm proper functioning of heart rate, skin temperature, and core temperature sensors before subjects left for their fire line work-shift. Heart rate, core temperature, and skin temperature were all continuously monitored by the Equivital system throughout the work shift and logged on the internal memory of the EQ02 SEM. After shift completion, the Equivital monitoring systems were collected from the subjects for raw data collection via USB download from the EQ02 SEM.

Weather (WLFF)

The dates of data collection for the two crews used ranged over six days, from June 13th – June 18th, 2012. During that time period, the working conditions averaged at $27.4\text{ }^{\circ}\text{C} \pm 3.61\text{ }^{\circ}\text{C}$, with a wind speed averaging at $6.5\text{ mph} \pm 3.0\text{ mph}$. All data was reported by Colorado State University's weather station in Fort Collins, CO.

Mount Evans Ride

The second field study (denoted "Mount Evans Ride") consisted of data collected during a 28 km ascending ride up Mount Evans near Idaho Springs, Colorado.

Subjects (Mount Evans Ride)

Subjects ($n=12$; age: 27.9 ± 4.6 ; height: $178.8 \pm 5.2\text{ cm}$; weight: $76.9 \pm 9.9\text{ kg}$; VO_2max : $4.5 \pm 0.6\text{ L} \cdot \text{min}^{-1}$) were recruited prior to the study and informed of the procedures and risks of participating in the study. Subjects then signed an institutional review board approved consent form and successfully completed the PAR-Q. Subjects conducted a VO_2max test on a Velatron

(Seattle, WA) cycle ergometer consisting of a progressive workload starting at 95 watts and increasing by 35 watts every three minutes until volitional fatigue to obtain $VO_{2\max}$. Expired gases were measured during the test using a calibrated Parvomedic TrueOne 2400 metabolic cart (Parvomedics, Inc., Salt Lake City, UT.) $VO_{2\max}$ was assigned to the highest achieved oxygen uptake recorded during the test and peak was calculated based upon the time spent at the highest power output achieved during the test.

Physiological Monitoring (Mount Evans Ride)

On the day of their field test, subjects reported to our site shortly after waking, and before their first meal. Subjects were fitted with a Polar heart rate monitor (Polar Electro Inc., Lake Success, NY), a VitalSense Dermal Skin Patch (Philip Respironics, Bend, OR), and an iButton (Maxim Integrated, San Jose, CA) temperature thermistor. A VitalSense core temperature capsule (Philip Respironics, Bend, OR) was activated, synced with the VitalSense monitoring system, and then ingested by the subject. Subjects performed the ascending ride at their controlled power output (50% max watts), self-monitored by viewing a CycleOps Powertap (Madison, WI) for a total exercise time of 138 ± 13 min over approximately 28 kilometers. During the ride, heart rate was collected continuously in 5 second intervals via a Polar RS300x (Polar Electro Inc., Lake Success, NY) watch and the heart rate at each minute was used for analysis. Core and skin temperature were collected continuously via the VitalSense monitoring system (both core and skin), and the iButton. This monitoring system differs from what was used in the WLFF study. A change was made due to the lack of reliable core temperature pill measurements by the Hildalgo system, as well as blue-tooth connection issues for ease of download. The iButton technology was used to search for an alternative to the Hildalgo system, and the temperature measurements were continuously validated by the VitalSense skin temperature patch. After completion of the ride, the monitoring systems remained attached to the subject for other

purposes, but end times for each subject were noted in order to identify the data that was collected during their ascension.

Weather (Mounts Evans)

The dates of data collection for the two groups of cyclists ranged over four days: August 4th-5th, and August 11th-12th, 2012. The riding conditions for August 4th included an average temperature of $12.5^{\circ}\text{C} \pm 7.1^{\circ}\text{C}$, with an average wind speed of $6.2 \text{ mph} \pm 5.7 \text{ mph}$. The riding conditions for August 5th included an average temperature of $12.3^{\circ}\text{C} \pm 7.0^{\circ}\text{C}$, with an average wind speed of $6.2 \text{ mph} \pm 5.8 \text{ mph}$. The riding conditions for August 11th included an average temperature of $17.4^{\circ}\text{C} \pm 6.0$, with an average wind speed of $0.5 \text{ mph} \pm 1.1 \text{ mph}$. The riding conditions for August 12th included an average temperature of $21.0^{\circ}\text{C} \pm 5.0^{\circ}\text{C}$, with an average wind speed of $0.2 \text{ mph} \pm 0.7 \text{ mph}$.

Calculations of PSI and PSS

All data was sorted into minute by minute values for core temperature, skin temperature, and heart rate. There were 29 subject days from the WLFF, and 12 subject days from the Mount Evans ride.

Physiological strain was calculated for each subject day minute by minute using the gold standard equation from Moran et al.:

$$\text{PSI} = 5(\text{T}_{\text{core}(t)} - \text{T}_{\text{core}(0)}) \cdot (39.5 - \text{T}_{\text{core}(0)})^{-1} + 5(\text{HR}_{(t)} - \text{HR}_{(0)}) \cdot (180 - \text{HR}_{(0)})^{-1}$$

Due to pre exercise anxiety and field conditions, consistent resting heart rates were not obtained, so a resting heart rate ($\text{HR}_{(0)}$) of 71 bpm was used for all calculations. Also, resting core temperatures were not obtained; therefore a resting core temperature ($\text{T}_{\text{core}(0)}$) of 37.12°C was used. Both of these recommendations are presented in Moran et al. (25) based on the mean resting values for 100 subjects. Moran labels a PSI of 7 to be “High” strain. Furthermore, he

breaks down strain into 5 categories: No/little, Low, Moderate, High, and Very high. For the purpose of this study, the following groupings were made: No/Little= <2 , Low=2.0-4, Moderate= 4.0-6, High= 6.0-8, Very high= >8 . Using Microsoft Excel, the “countif $>$ or $<$ ” function is applied to each bordering zone, therefore discrimination between values that are close to the cut point is made and they are not counted in multiple bordering zones.

Physiological Strain Scale was also calculated minute-by-minute using the novel equations developed by WPEM. These results also follow the same groupings as noted above for PSI.

The unique comparison of average minute by minute agreement for the gold standard measurement of PSI vs. the novel measurement of PSS is presented. This novel technique will allow the direct comparison between the two models in a minute by minute fashion, allowing us to ascertain the differences, if any, between risks score, response times, and sensitivity of each model.

The minute by minute agreement between average T_{core} , average T_{skin} , and HR is also presented. To investigate the role of the environment on PSI and PSS, the $T_{core}-T_{skin}$ gradient was calculated, and graphed on a dual axis graph with average PSI and average PSS.

The number of minutes spent in each zone throughout the work day was compiled for comparison and contrast. The actual PSI time (min) in each defined zone is compared to PSS time (min) in each corresponding zone.

Statistical Analysis

WLFF

A 2x5 repeated measures ANOVA was used to assess differences in time spent at each zone of the gold standard PSI (assessed by HR and core temperature) and time spent at each zone of PSS (assessed based on HR and skin temperature). PSS was calculated using the novel equation for

warm ambient temperatures. The zones are defined as: No/Little= <2, Low=2.0-4, Moderate= 4.0-6, High= 6.0-8, Very high= >8.

Statistical significance was established using an alpha level of $p < 0.05$.

Mount Evans Ride

A 2x4 repeated measures ANOVA was used to assess differences in time spent at each zone of the gold standard PSI (assessed by HR and core temperature) and time spent at each zone of PSS (assessed based on HR and skin temperature). PSS was calculated using the novel equation for cool ambient temperatures. The zones are defined as: No/Little= <2, Low=2.0-4, Moderate= 4.0-6, High= 6.0-8. The uppermost zone of >8 was not be used, as subjects did not achieve results at this level. Statistical significance was established using an alpha level of $p < 0.05$.

Chapter Four: Results

WLFF

PSI and PSS

All subject's (N=29) data were collected in minute by minute fashion and reported as total collective minutes spent in the defined physiological strain ranges of No/Little= <2, Low=2-4, Moderate= 4-6, High= 6-8, Very high= >8. Minute by minute agreement between PSI and PSS can be seen in Figure 1.

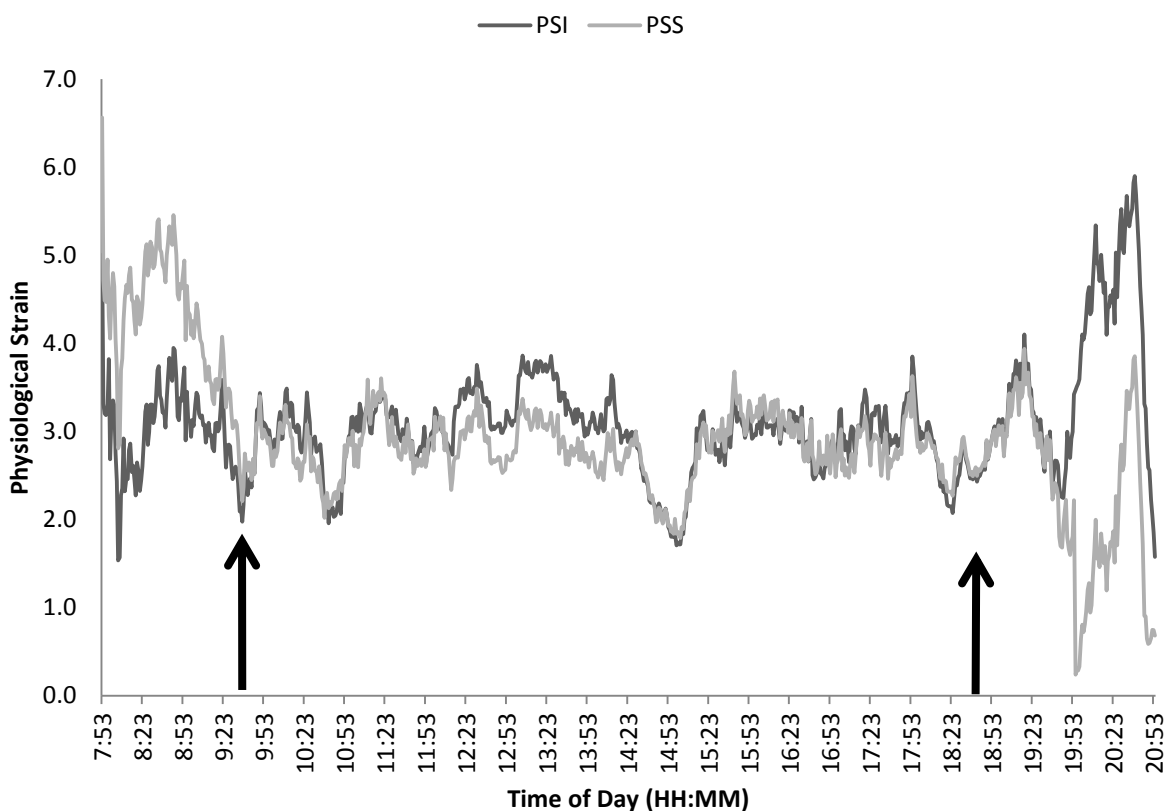


Figure 1: Comparison of Average PSI vs Average PSS Over a Single Workshift. Displays the minute by minute agreement between average PSI and average PSS during a single workshift. The black arrows indicate where a high percentage of skin or core temperature data points were lost.

As seen in Figure 1, the black arrows denote the area where the best agreement between PSI and PSS occurs. This is due to the high number of core temperature data points being lost, which affect both the average, and the range of the data. Therefore, for statistical analysis, the

workshift was cut down to these time points where the least amount of data was lost. This new agreement graph can be seen in Figure 2.

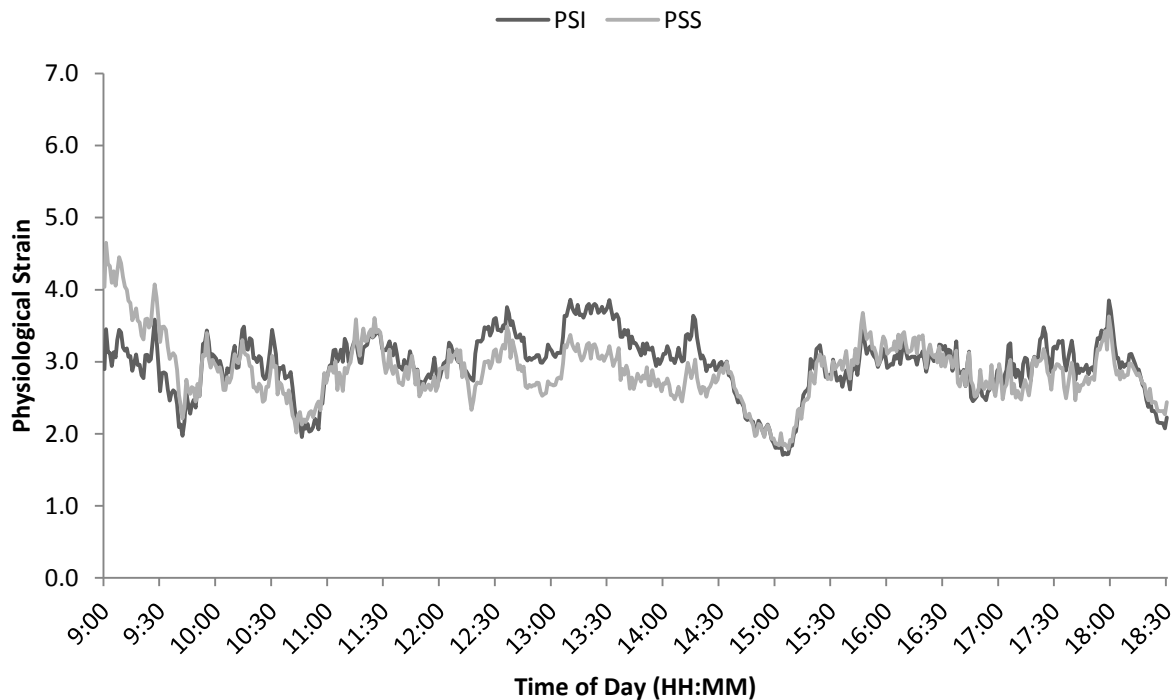


Figure 2: Comparison of Average PSI vs Average PSS Over a Single Workshift- Adjusted for Start Times. The agreement between average PSI and PSS over an adjusted workshift that begins at 9:00 am, and ends at 6:30 pm. This adjustment was made due to dropped core data points in the majority of the subjects before/after these time points to for visual purposes.

Average time spent at each PSI ranges were calculated and reported as mean \pm standard deviation (198 \pm 145 min, 256 \pm 121 min, 162 \pm 95 min, 33 \pm 35 min, and 0.8 \pm 2.8, respectively.)

Average time spent at each PSS ranges were calculated and reported as mean \pm standard deviation (196 \pm 122 min, 259 \pm 89 min, 143 \pm 92 min, 39 \pm 36 min, and 5 \pm 9 min, respectively.)

Using a 2 x 5 ANOVA with a Bonferroni adjustment for multiple comparisons, agreement between PSI and PSS was tested. As can be seen in Figure 3, there is no interaction and no main effect for method of heat stress calculation between PSI and PSS. However, there was a main effect for time spent in each physiological strain zone. This is best shown by the comparison of percentages in Table 1. Subjects spent the most time in the 2.0-4 (“b”) zone (PSI, PSS: 39.4%, 40.4%), followed by the <2 zone (30.4%, 30.5%), then the 4.0-6 zone (25.0%, 22.2%), followed

by the 6-8 zone (5.1%, 6.1%), and finally the >8 ranges (0.1%, 0.8%) ($p < 0.05$). There is no significant difference between the time spent in the 2.0-4 range and the <2 range ($p > 0.05$). The time spent at a PSI or PSS that would cause concern (5.2%, and 6.9%, respectively) was minimal, and as depicted in Figure 1, occurred at the onset of work, and the completion of their day.

Figure 4 depicts the variations in T_{core} , T_{skin} and HR over the course of the workshift. Although the T_{skin} appears to be lower than T_{core} throughout the day, there was no statistical difference between the methods for calculating heat strain. Figure 3 also depicts the varying HR, which demonstrate work/rest cycles and changes in work intensity.

In Figure 5, the agreement between average PSI and Average PSI is depicted, as well as the role the T_{core} - T_{skin} gradient plays in this agreement. Throughout the entire workshift, the gradient was no more than 2°C in difference.

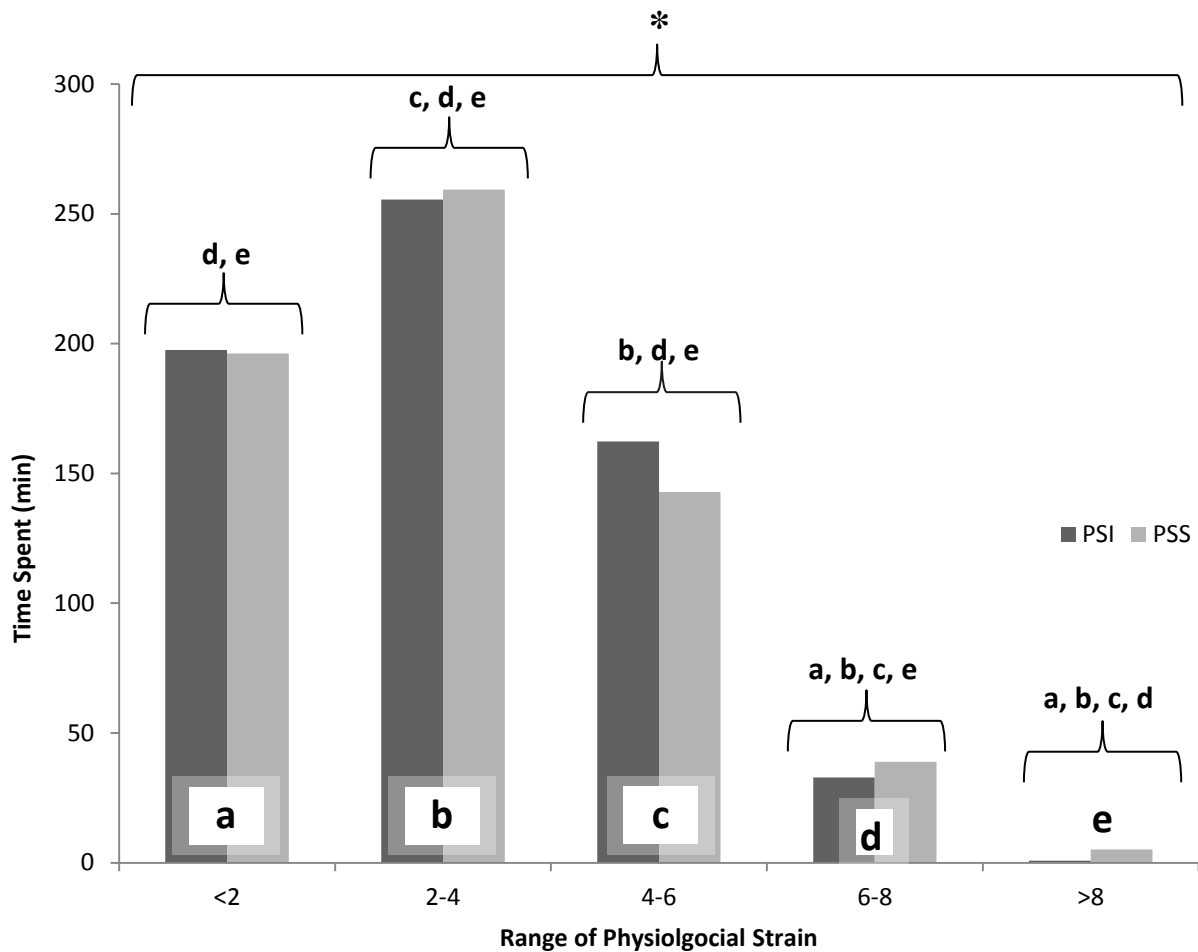


Figure 3: PSI vs PSS Average Time Spent Within the Given Ranges of Physiological Strain Over a Single Workshift. Comparison of the average time spent in each physiological strain range as measured by PSI versus PSS. There is no statistical difference between PSI and PSS at each given range. There is a main effect for time spent in each range. Range “a” is statistically different than ranges d and e ($p<0.05$). Range b is statistically different than ranges c, d and e ($p<0.05$). Range c is statistically different than ranges b, d, and e ($p<0.05$). Range d is statistically different than ranges a, b, c, d, and e ($p<0.05$). Range e is statistically different than ranges a, b, c, and d ($p<0.05$). * No main effect for method of heat stress calculation

	>2	2.0-4	4.0-6	6.0-8	>8
	a	b	c	d	e
PSI	30.4%	39.4%	25.0%	5.1%	0.1%
PSS	30.5%	40.4%	22.2%	6.1%	0.8%

Table 1: Percentage of total time spent at each given physiological strain zone. There is a main effect for time spent in each zone, as depicted by the percentages. The 2.0-4 zone accrued the most time, followed by the >2 zone, the 4.0-6 zone, the 6.0-8 zone, and the >8 zone ($p<0.05$). There was no statistical difference between the >2 zone and the 2.0-4 zone ($p>0.05$).

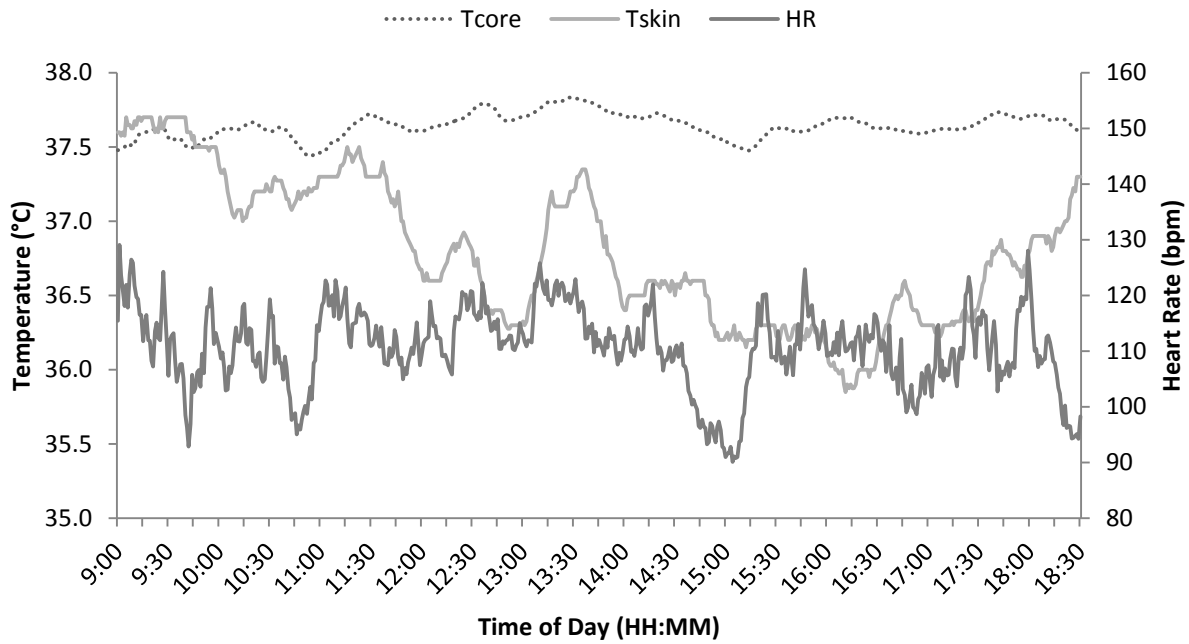


Figure 4: Comparison of Average HR, T_{core}, and T_{skin} responses Over a Single Adjusted Workshift. Variations in T_{core} and T_{skin} as compared to heart rate response during a single workshift. T_{skin} is consistently lower than T_{core} throughout the day, yet the ability of PSS (T_{skin}) to predict strain was not affected. Variations and elongated plateaus in heart rate may be indicative of self-mediated work rest cycles.

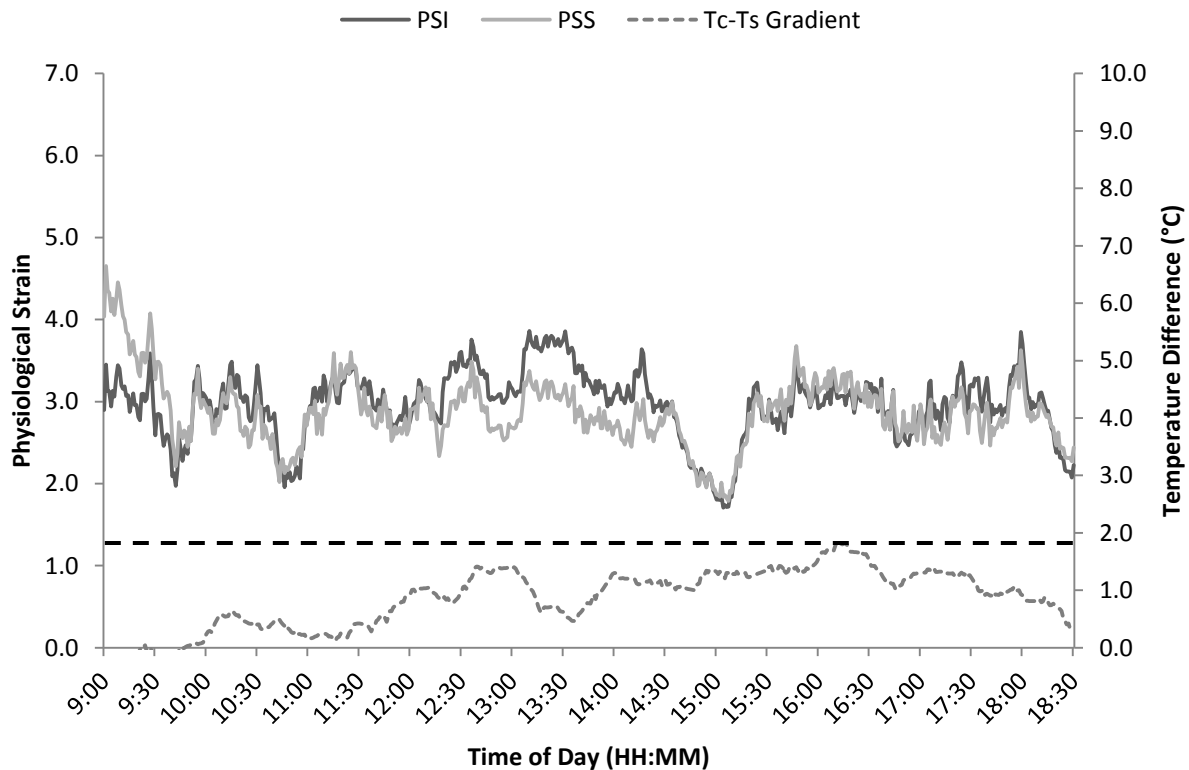


Figure 5: Response of Average PSI and Average PSS to Core-Skin Temperature Gradient. The agreement between average PSI and PSS compared to the T_{core}-T_{skin} gradient over the adjusted work shift. Due to the low (<2) temperature gradient, PSS is able to measure physiological strain as accurately as PSI.

Mount Evans Ride

PSI and PSS

All subject's (N=12) data were collected in minute by minute fashion, and reported as total collective minutes spent in the defined physiological strain ranges of No/Little= <2, Low=2-4, Moderate= 4-6, High= 6-8. The range of "Very High= >8" was excluded from statistical analysis because subjects did not reach any time points at this risk category. For this field study, there were two trials conducted. One trial included the ingestion of a known stimulant, while the other trial was a placebo. As can be seen in Figure 6, there is a disagreement between PSI and PSS for both the Drug and the Placebo (PLA) trial. However, there is agreement between PSS and PSI to themselves, no matter the trial. Unfortunately, of the 12 subjects that underwent the drug trial, only 4 subjects had enough T_{core} data for statistical analysis. The drug trial was dropped because of the low "n" value. The disagreement between average PSI and average PSS throughout the ascension is depicted in Figure 7.

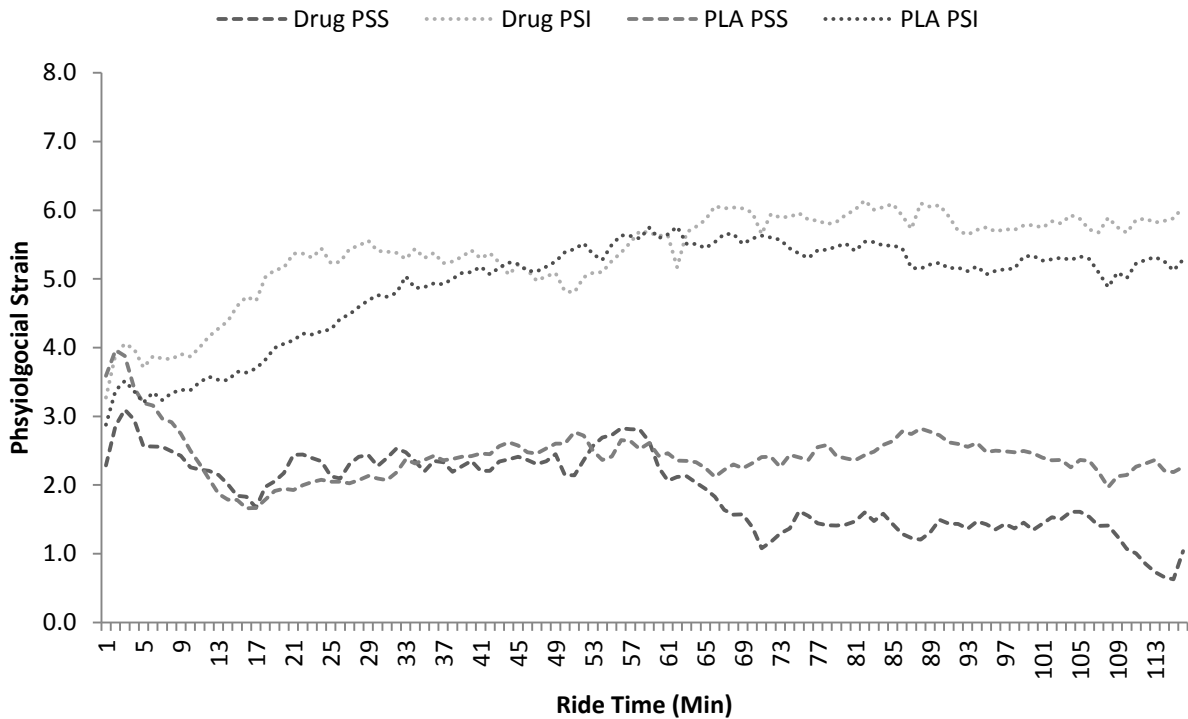


Figure 6: Comparison of Average PSI vs Average PSS for combined Drug and Placebo Trials. Disagreement between Drug PSS and Drug PSI, as well as Placebo (PLA) PSS and PSI. There appears to be agreement between PLA PSS and Drug PSS, as well as PLA PSI and Drug PSI.

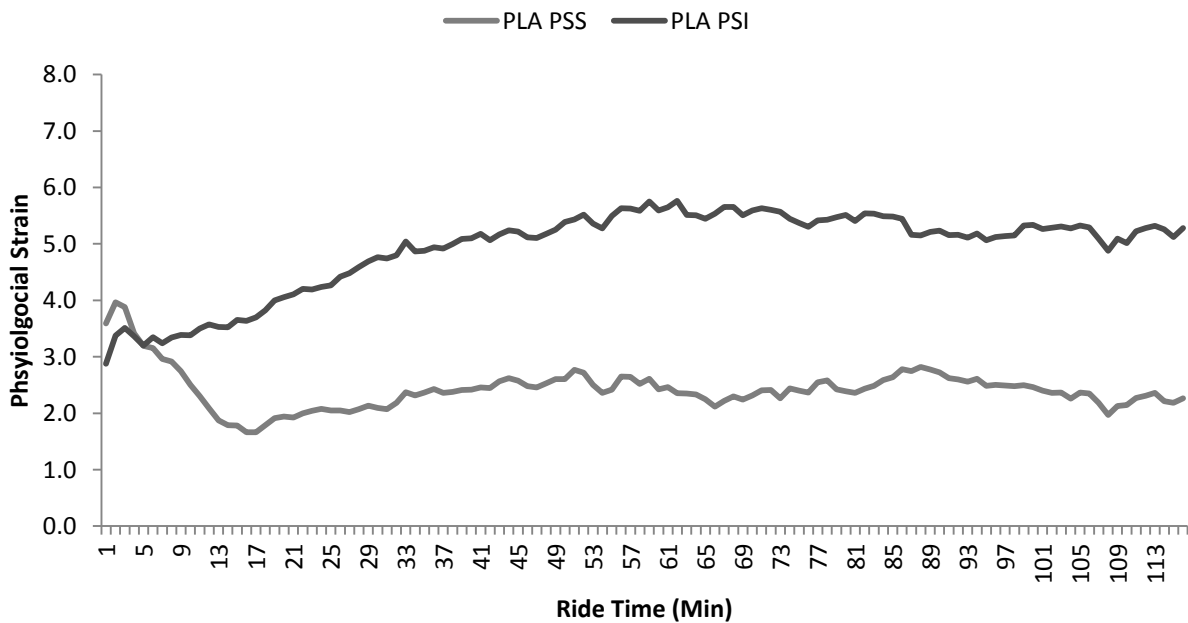


Figure 7: Comparison of Average PSI vs Average PSS for Placebo Trial. Disagreement between average PSI and average PSS in the placebo trail (N=12). This shows the consistent, yet obviously different responses in PSI vs PSS throughout the ascension.

To assess this disagreement, average time spent at each PLA PSI ranges were first calculated and reported as mean \pm standard deviation (1 ± 1.7 , 29 ± 23.9 , 67 ± 29.4 , and 36 ± 40.2 , respectively.) Average time spent at each PLA PSS ranges were also calculated and reported as mean \pm standard deviation (54 ± 46.7 , 59 ± 34.4 , 24 ± 30.4 , and 0 ± 0.4 , respectively.)

Using a 2 x 4 ANOVA with a Bonferroni adjustment for multiple comparisons, agreement between PLA PSI and PLA PSS was tested. As can be seen in Figure 6, there are significant differences between PSI and PSS at all ranges of physiological strain rating ($p < 0.05$), except for the 2-4 (“b”) range ($p = 0.056$) where there is only a significant trend present. Therefore, there is statistically significant disagreement between PSI and PSS throughout the ascension during the placebo trail, which was depicted in Figure 8.

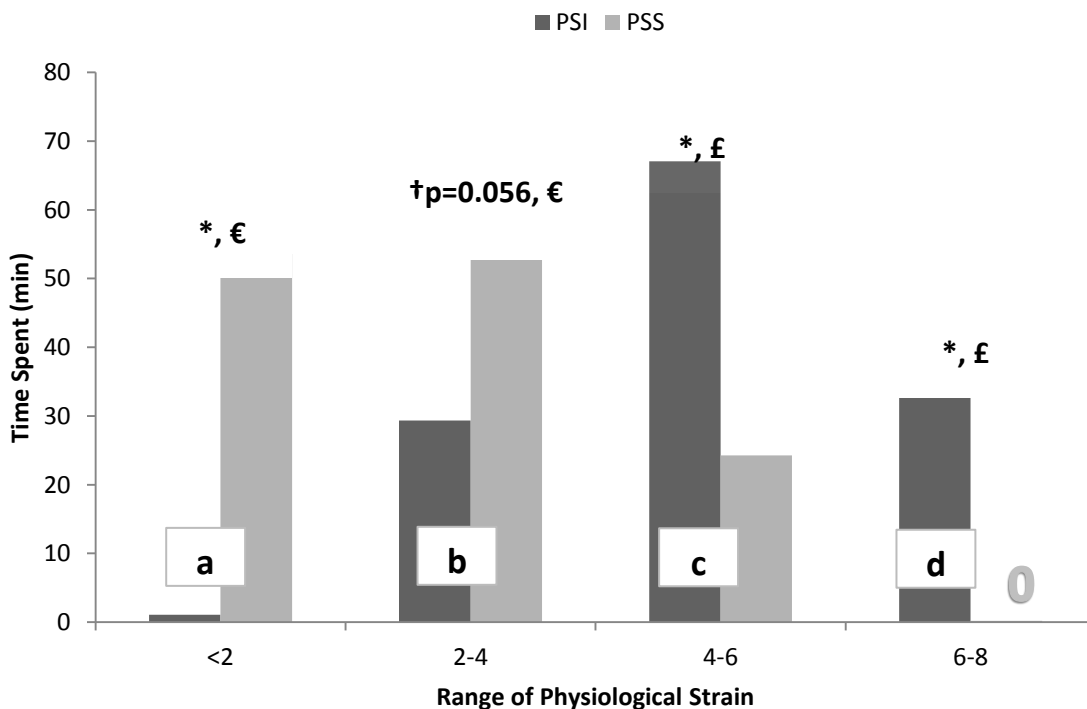


Figure 8: PSI vs PSS Average Time Spent Within the Given Ranges of Physiological Strain. Comparison of the average time spent in each physiological strain range as measured by PSI versus PSS. There is a significant interaction between PSI and PSS at all ranges, except 2-4 ($p = 0.056$). *Denotes significant difference between PSI and PSS ($p < 0.05$). †Denotes a trend towards significant difference between PSI and PSS ($p = 0.056$) £ Denotes ranges with significantly higher time spent for PSI ($p < 0.05$). € Denotes ranges with significantly higher time spent for PSS ($p < 0.05$).

In order to explain the disagreement, T_{core} data was compared vs. PSI data, as well as T_{skin} data compared to PSS, graphically. These comparisons can be seen in Figure 9 and Figure 10. Figure 12 shows the disagreement between T_{core} and T_{skin} , and how that disagreement can be represented by the $T_{core}-T_{skin}$ gradient that was calculated in WLFF. This gradient was between 5°C and 7°C in this subject group, which was much higher than the WLFF group. An overlay graph showing the role of the $T_{core}-T_{skin}$ gradient on the agreement between PSI and PSS between the two subject groups can be seen in Figure 13.

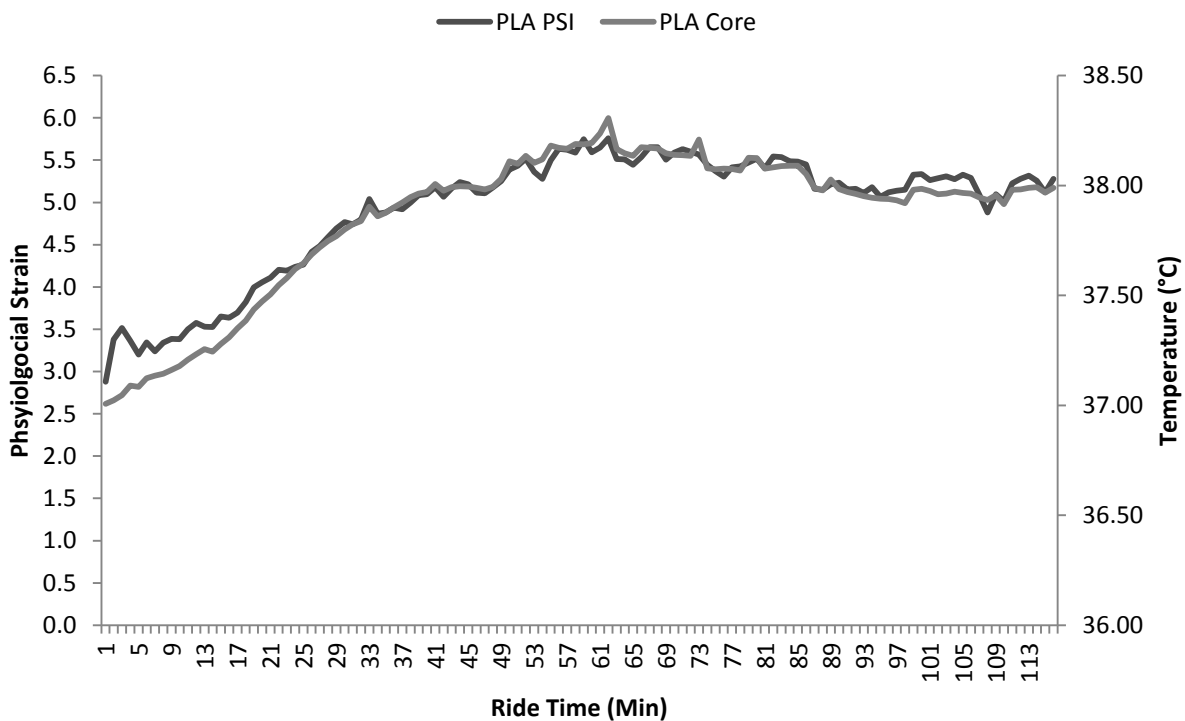


Figure 9: Comparison of Average PSI vs Average Tcore during the Placebo Trial. Comparison of Average PSI to Average T_{core} during the Placebo Trial. Demonstrates the agreement between T_{core} and PSI throughout the Mount Evans Ride.

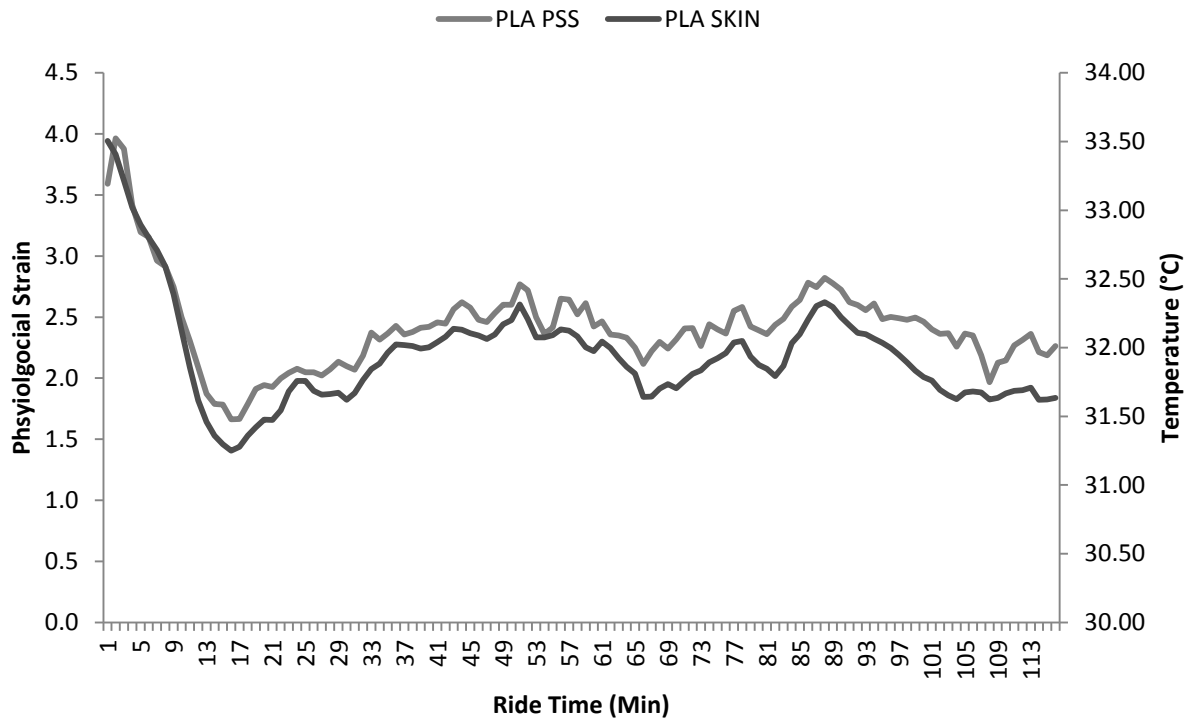


Figure 10: Comparison of Average PSS vs Average T_{skin} during the Placebo Trial. Comparison of Average PSS to Average T_{skin} during the Placebo Trial. Demonstrates the agreement between T_{skin} and PSS throughout the Mount Evans Ride

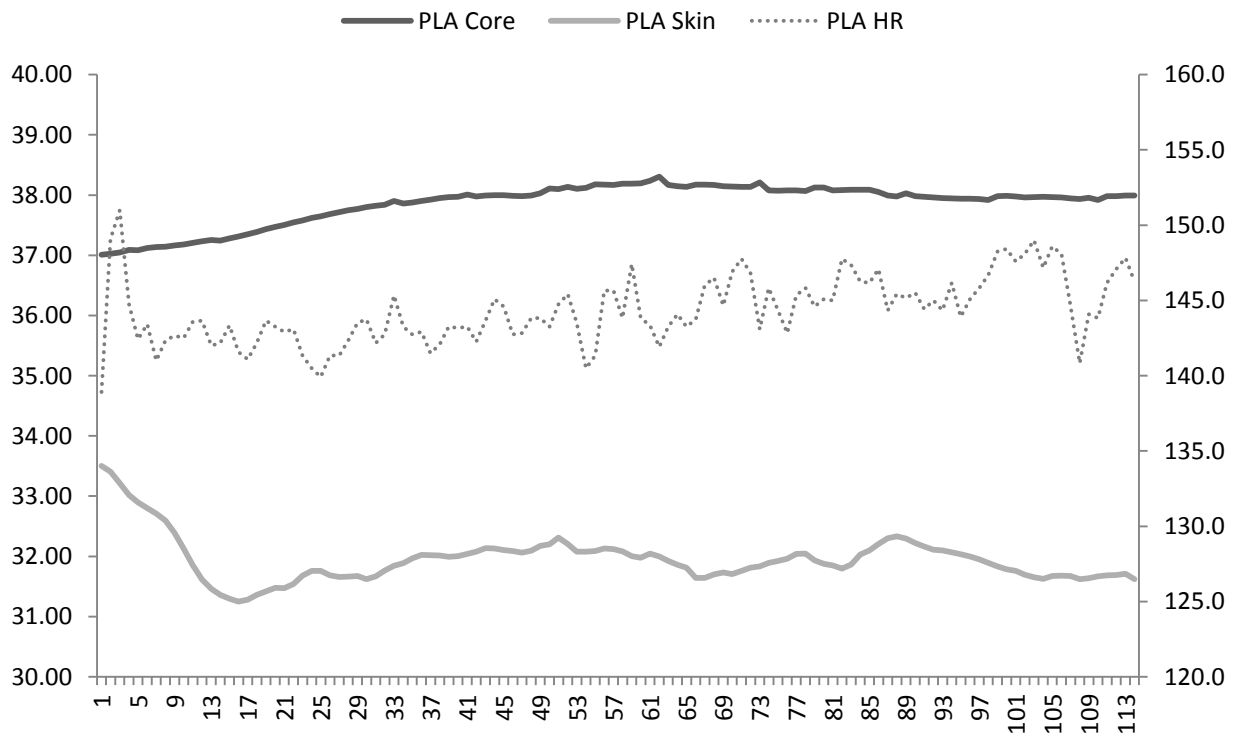


Figure 11: Comparison of Average HR, T_{core}, and T_{skin} responses during an Ascension Ride. Variations in T_{core} and T_{skin} as compared to HR response during an ascension ride. T_{skin} is consistently >3°C lower than T_{core} throughout the ride, which may account for the difference between PSS and PSI. A fairly constant HR is observed due to the individually prescribed workload throughout the ride.

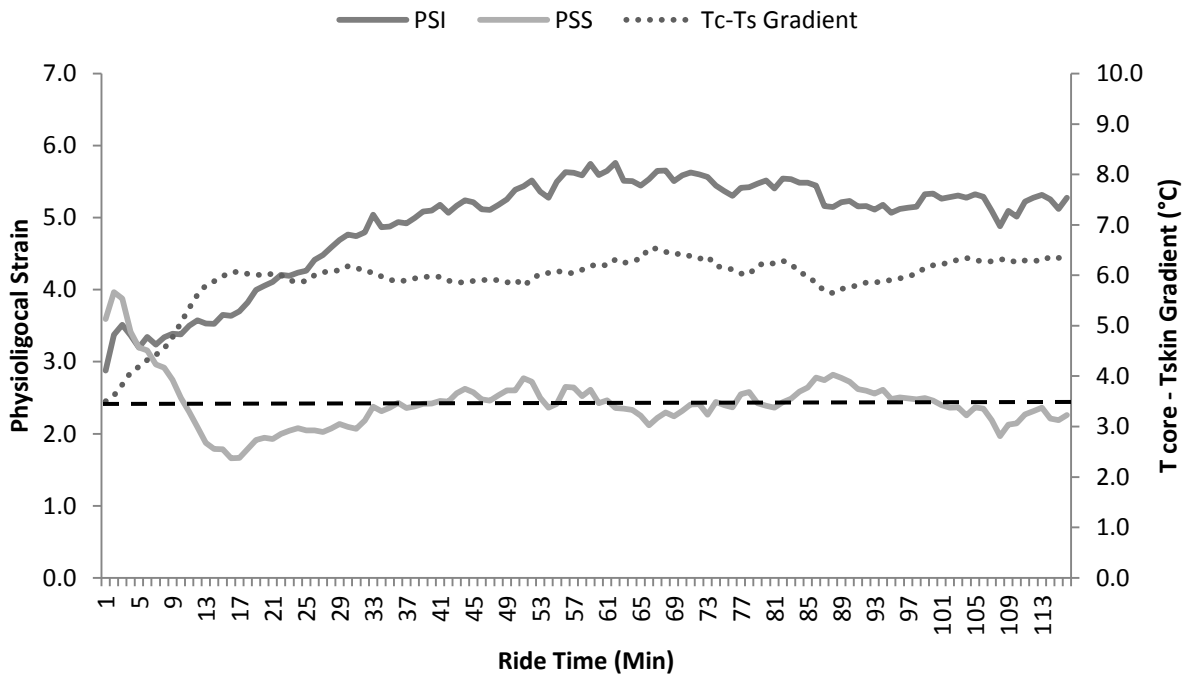


Figure 12: Comparison of Average PSI and Average PSS to Core-Skin Temperature Gradient. The comparison of Average PSS and Average PSI to the calculated $T_{Core}-T_{skin}$ temperature gradient. This demonstrates the high range differences ($>3.5\text{ }^{\circ}\text{C}$ at each time point) between T_{core} and T_{skin} , which accounts for the lack of agreement between PSI and PSS.

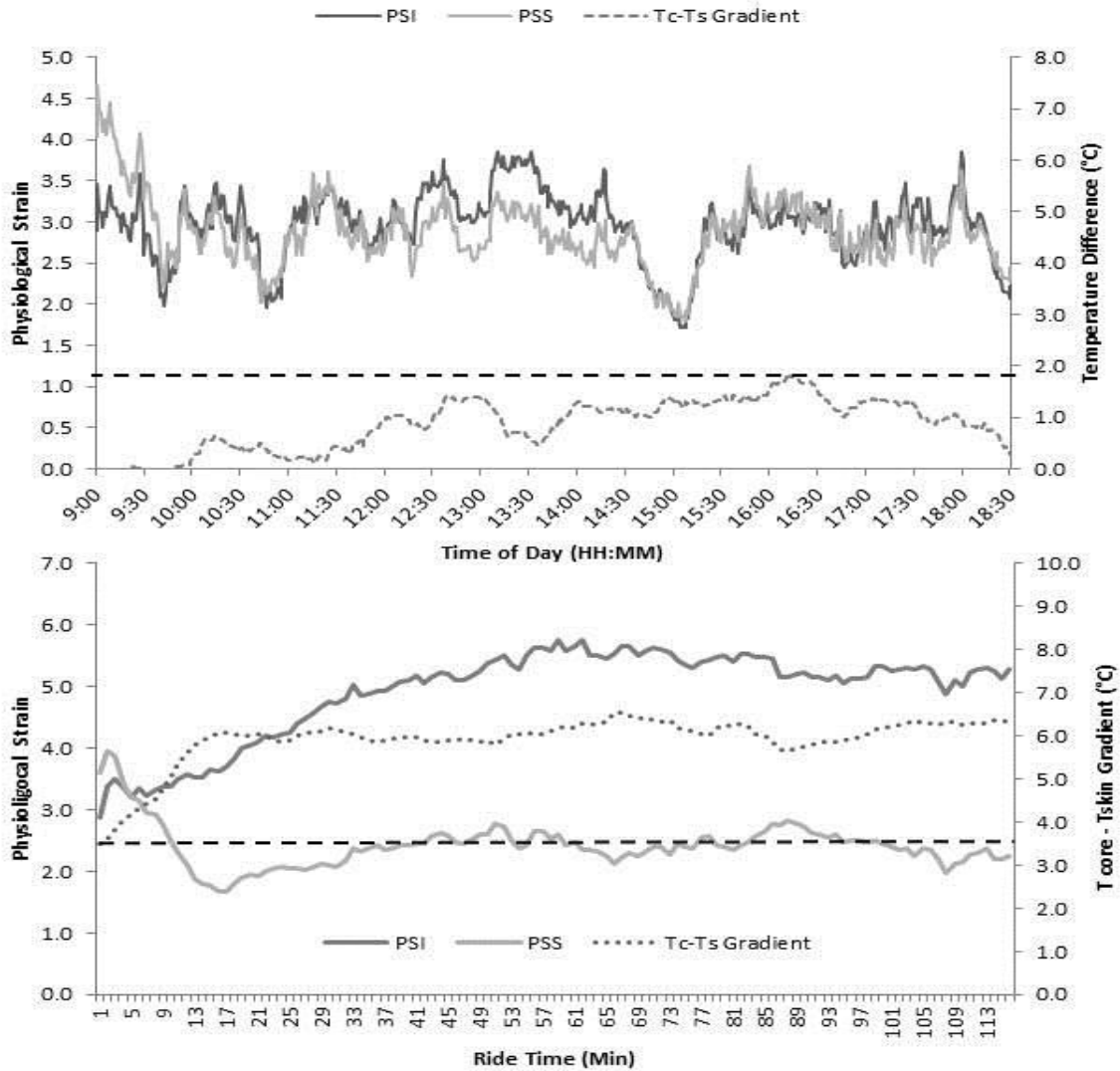


Figure 13: Comparison of agreement in relationship to $T_{core}-T_{skin}$ gradient for each subject pool. The agreement between average PSI and PSS vs. the $T_{core}-T_{skin}$ gradient over the adjusted work shift compared to the agreement between average PSI and PSS vs. the $T_{core}-T_{skin}$ gradient for the Mount Evans Ride.

Chapter Five: Discussion

WLFF

The purpose of our efforts in this study was to evaluate the accuracy and reliability of our novel PSS equation when compared to the gold standard model of PSI. In this field study, our subjects were immersed into a hazardous environment as a factor of their job duties. This environment is considered to be uncompensable because of the inability of subjects to be able to cool via evaporation of sweat, convection, or radiation. As mentioned previously, the rationale for using an equation that relies on skin temperature measurements, rather than core temperature measurements, comes from the heat balance equation seen below (2, 14).

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

S = the rate of body heat storage, M = the rate of metabolic energy production, W= mechanical work, R+C = the rate of radiant and convective energy exchanges, respective, and E= rate of evaporative loss.

Due to the environment that our subjects were in, the ability to dissipate metabolic heat via radiant and convective energy exchange, as well as through evaporation, were extremely minimal. Therefore, the body is shunting extra blood to the skin to desperately try to regulate metabolic heat production, allowing us to accurately measure the risk for heat strain based upon these changes in skin temperature (14). This phenomenon can be depicted by Figure 4 and Figure 5. In Figure 4, we see the variations between T_{core} and T_{skin} responses in this environment. Heart rate is also extremely variable, with noticeable work/rest cycles. However, despite the slight variations in skin temperature when compared to core, PSS was still able to predict physiological strain as effectively as PSI. Figure 5 shows the agreement between PSS and PSI throughout our “adjusted” time period, as well as the gradient between T_{core} and T_{skin} . This graph suggests that in high heat, high risk environments where there is a very low gradient between T_{core} and T_{skin} , and the most need for a reliable measurement for the safety of the workers, PSS gives us the confidence to accurately monitor subject’s risk as effectively as PSI.

We also discovered a main effect for time spent in each range, as seen in Figure 3. Despite the high ambient temperatures and the hazardous work environment, it appears that subjects were able to mitigate their heat stress levels effectively throughout the duration of their work shift. For both PSI and PSS, subjects spent significantly more time at the lower level ranges (<2, 2-4, 4-6) than in the upper, at risk ranges (6-8, >8) ($p < 0.05$). This phenomenon can also be explained by the heat balance equation. Since subjects were not able to cool themselves adequately through convection, radiation, or evaporation due to their work environment, they only other variables to manipulate are metabolic heat production and workload (2, 14). Previous data (5, 22, 32) have also demonstrated the effects of environment on thermoregulation. When the body is unable to cool due to the environment, the subject must regulate their intensity or workload to adequately combat heat stress. As discussed in a case study done by Cuddy *et al.*, this combination of continuous high work output and a high ambient temperature (arduous) environment can be deadly, even with proper hydration (9, 29).

Furthermore, it is suggested by our data that subjects adequately mitigated their heat stress levels through self-selected workload practices (as shown by HR intervals in Figure 8), in which the type of work, and/or work-rest cycles were controlled by the subjects in an innate fashion, which seemed to provide adequate protection in the heat for the majority of their workshift. However, despite their learned precautions, subjects still spent roughly 7% of their total time in the 6-8 and >8 ranges (TT= 634 minutes). This becomes a concern since there is no knowledge of how much exposure at these upper ranges is safe. Although this 7% did not result in a HRI event on this given day, further research needs to be done in order to accurately quantify how long in an at risk environment is too long.

Mount Evans Ride

In this field study, the ambient environment varies greatly from the harsh environment studied in the WLFF. The cooler temperatures, use of breathable clothing, and wind movement all attest to the differences we see in the Mount Evans Ride. As seen in Figure 8, there are significant differences between PSI and PSS and ranges <2, 4-6, and 6-8 ($p < 0.05$). These differences could be attributed to a number of factors. First, there is a large range value within our data due to the rapid ability of skin temperature to cool through evaporation. This difference in monitoring systems can be seen in Figure 9 and Figure 10. In Figure 9, we can see the agreement between T_{core} and PSI, as PSI is calculated from T_{core} . The same agreement is shown for T_{skin} and PSS in Figure 10. The variations between the two methods of heat stress calculation come from the large gradient between T_{core} and T_{skin} , which is shown in Figure 12. When compared to the gradient achieved in the WLFF study (never above 2.0 °C difference), the Mount Evans study had a much larger $T_{core}-T_{skin}$ gradient (consistently between 5°C to 7°C difference) (see Figure 13). This larger gradient is a variable of the environment, and the ability of that environment to accept metabolic heat from the subject through convection, radiation and evaporation. It is not a function of metabolic workload as seen in the WLFF. This has been shown by the classification models by Buller *et al.* and Cuddy *et al.*, where physiological strain risk was correctly identified by PSS in presence of a low T_{skin} , but a high HR (3, 5). It is the combination of a high T_{skin} and a high HR that reflects the environment, and the metabolic workload which ultimately leads to the increased risk for HRI (3, 5, 14).

Therefore, the responsiveness of PSS is better represented by our data, and demonstrates one of the limitations of PSI. Since the environments that the subjects are exposed to are not completely uncompensable, there will be variability in skin temperature responses, which is accurately depicted by PSS in both environments. As previously mentioned, core temperature responses to

the environment are significantly less than the response of skin temperature, which is demonstrated in Figure 9 and Figure 10 (7, 15, 23). Our data suggests that PSI over predicts subject's risk for HRI in this type of environment due to its lack of responsiveness to a cooler ambient temperature and wind speed. It is the ability of the body to dissipate metabolic heat through convection and evaporation that will provide the greatest protection from HRIs (2, 10, 13, 14). Thusly, this data supports the theory that PSS is a much more responsive, and accurate representation of true heat related illness risk in a dynamic, and cooler environment.

Conclusion

The primary goal of this study was to determine if the novel PSS equation developed by WPEM accurately and reliably predicted physiological strain when compared to the gold standard measurement of PSI. Two data sets were used to test this theory, both of varying workloads and environment. When put through the rigors of a high heat, high risk environment (WLFF) PSS did accurately and reliably predict physiological strain when compared to PSI ($p>0.05$). Although this was not the case in the Mount Evans Ride, the data suggests that PSS provides a better representation of physiological strain in a cooler environment than PSI does. All in all, PSS provides us with an accurate and reliable way to monitor a subject's physiological strain in any given environment, while being less invasive and more cost effective than the previous accepted gold standard model of PSI.

References

1. Belding, H. S. The search for a universal heat stress index. In: *Physiological and Behavioral temperature Regulation*, J. D. Hardy, A. P. Gagge, and J. J. Stolwijk (Eds.). Chicago: Charles C Thomas, 1970, pp. 193-202
2. Brotherhood JR. Heat stress and strain in exercise and sport. *Journal of Science and Medicine in Sport*, 11, 6-19, 2008.
3. Buller MJ, Latzka WA, Yokota M, Tharion, WJ and Moran DS. A real time heat strain risk classifier using non-invasive measures of heart rate and skin temperature. *Physiological Measurement*, 29(12), N79-85, Dec 2008.
4. Castellani JW, FASCM. Perceptual cold index vs. physiological cold strain index during exercise-cold stress. *Med Sci Sports Exerc*, 35(5), Supplement 1, p S24, 2003.
5. Cuddy JS, Buller M, Hailes WS, Ruby BC. Skin temperature and heart rate can be used to estimate physiological strain during exercise in the heat in a cohort of fit and unfit males. *Pending publication in Mil Med 2013*.
6. Cuddy, J., Ruby, BC. High work output combined with high ambient temperatures caused heat exhaustion in a wildland firefighter despite high fluid intake. *Wilderness & Environmental Medicine*, 22, 122-125, 2011.
7. Cuddy JS, Ruby BC, Santee WR, Karis AJ. USARIEM Technical Report T09-02: Hidalgo Equivital Physiological Monitor Product Review and Data Summary. *U.S. Army Research Institute of Environmental Medicine: Biophysics and Biomedical Modeling Division*. December, 2008.
8. Easton C, Fudge BW and Pitsiladis YP. Rectal, telemetry pill and tympanic membrane thermometry during exercise heat stress. *J Therm Biol*, 32, 78-86, 2007.
9. Fox CA, Meldrum SJ and Watson BW. Continuous measurement by radio-telemetry of vaginal pH during human coitus. *J Reprod Fertil*, 33, 69-75, 1973.
10. FRANK, A., D. MORAN, Y EPSTEIN, M. BELOKOPYTOV, AND Y SHAPIRO. The estimation of heat tolerance by a new cumulative heat strain index. In: *Environmental Ergonomics: Recent Progress and New Frontiers*, Y. Shapiro, D. Moran, and Y. Epstein (Eds.). London: Freund, 1996, pp. 194-197.
11. Gonzalez RR, McLellan TM, Withey WR, Chang SK and Pandolf KB. Heat strain models applicable for protective clothing systems: comparison of core temperature response. *J Appl Physiol*, 83(3), 1017-1032, 1997.
12. Gunga HC, Sandsund M, Reinertsen RE, Sattler F and Koch J. A non-invasive device to continuously determine heat strain in humans. *J Therm Biol*, 33, 297-307, 2008.
13. Gunga HC, Werner A, Stahn A, Steinach M, Schlabs T, Koralewski E, Kunz D, Belavy DL, Felsenber D, Sattler F and Kock J. The double sensor- a non-invasive device to continuously monitor core temperature in humans on earth and in space. *Respiratory Physiology and Neurobiology*, 169S, S63-S68, 2009.
14. Kamon E, Soto K and Benson J. Physiological responses to high radiant heat exposure. *Environmental Research*, 28, 96-105, 1982.
15. Kenefick RW, Chevront SN, and Sawk MN. Thermoregulatory function during the marathon. *Sports Med*, 37(4-5), 312-315, 2007.
16. Kolka MA, Quigley MD, Blanchard LA, Toyota DA and Stephenson LA. Validation of a temperature telemetry system during moderate and strenuous exercise. *J Therm Biol*, 18(4), 203-210, 1993.

17. Krake AM, McCullough JE, King SB. Health Hazard Evaluation Report 2000-0061-2885. Department of Health and Human Services, Centers for Disease Control. December 2002. Accessed 9-25-12. <http://www.cdc.gov/niosh/hhe/reports/pdfs/2000-0061-2885.pdf>
18. Lucas SJ, Anglem N, Roberts WS, Anson JG, Palmer CD, Walker RJ, Cook CJ and Cotter JD. Intensity and physiological strain of competitive ultra-endurance exercise in humans. *Journal of Sports Sciences*, 26(5), 477-489, 2008.
19. Lumingu HMM and Dessureault P. Physiological responses to heat strain: a study on personal monitoring for young workers. *J Therm Biol*, 34, 299-305, 2009.
20. Matthew CB, Bastille AM, Gonzalez RR, Sils IV and Hoyt RW. Heart rate variability as an index of physiological strain in hyperthermic and dehydrated rats. *Journal of Thermal Biology*, 29, 211-219, 2004.
21. Mckenzie JE and Osgood DW. Validation of a new telemetric core temperature monitor. *J Therm Biol*, 29, 605-611, 2004.
22. Montain SJ, Sawka MN, Cadarette BS, Quigley MD and McKay JM. Physiological tolerance to uncompensable heat stress: effects of exercise intensity, protective clothing, and climate. *J Appl Physiol*, 77, 216-222, 1994.
23. Moran DS and Mendal L. Core temperature measurement: methods and current insights. *Sports Med*, 32(14), 879-885, 2002.
24. Moran DS, Pandolf KB, Shapiro Y, Laor A, Heled Y and Gonzalez RR. Evaluation of the environmental stress index for physiological variables. *J Therm Biol*, 28, 43-49, 2003.
25. Moran DS, Shapiro Y, Laor A, Izraeli S, Pandolf KB. Can gender differences during exercise-heat stress be assessed by the physiological strain index? *Am J Physiol Regul Integr Comp Physiol*, 276, R1798-R1804, 1999.
26. Moran DS, Shitzer A and Pandolf KB. A physiological strain index to evaluate heat stress. *Am J Physiol Regul Integr Comp Physiol*, 275, R129-R134, 1998.
27. ROBINSON, S., E. S. TURELL, AND S.D. GERKING. Physiological equivalent conditions of air temperature and humidity. *American Journal of Physiology*. 143:21-32, 1945.
28. Sawka MN, Young AJ, Latzka WA, Neuffer PD, Quigley MD and Pandolf KB. Human tolerance to heat strain during exercise: influence of hydration. *J Appl Physiol*, 73, 368-375, 1992.
29. Smith DL, Manning TS and Petruzzello SJ. Effect of strenuous live-fire drills on cardiovascular and psychological responses of recruit fire fighters. *Ergonomics*, 44(3), 244-254, 2001.
30. Tikuisis P, McLellan TM and Selkirk G. Perceptual versus physiological heat strain during exercise-heat stress. *Med Sci Sports Exerc*, 34(9), 1454-1461, 2002.
31. US Army 2011. *High Temperatures and Heat Related Injuries Can Go Hand in Hand*. <http://www.army.mil>, article 60097. Accessed 9/25/2012.
32. Wilkinson DM, Carter JM, Richmond VL, Blacker SD, Rayson MP. The effect of cool water ingestion on gastrointestinal pill temperature. *Med Sci Sports Exerc* 2008; 40: 523-528.
33. Yokota M, Berglund LG, Santee WR, Buller MJ, Karis AJ, Roberts WS, Cuddy JS, Ruby BC and Hoyt RW. Applications of real-time thermoregulatory models to occupation heat stress: validation with military and civilian field studies. *Journal of Strength and Conditioning Research*, 26(7), S37-S44, 2012.