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# Theoretical bases for a personal heat strain monitor

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# THEORETICAL BASES FOR A PERSONAL HEAT STRAIN MONITOR

A thesis submitted in partial fulfilment of the
requirements for the award of the degree

Masters of Science (Hons)
from
University of Wollongong

by

Karen Anne Armstrong
BExSc (Hons), BSc (Psychology)

Department of Biomedical Science
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I, Karen Anne Armstrong, declare that this thesis, is submitted in partial fulfilment of the requirements for the award of Master of Science (Hons), in the Department of Biomedical Science, University of Wollongong, is wholly my own work unless otherwise referenced or acknowledged. The document has not been submitted for qualifications at any other academic institution.

_______________________________ Date:______________

Karen Anne Armstrong

# ABSTRACT

Heat stress is a major consideration for a wide range of occupations including mining, construction and defence. Traditionally, heat stress equations have been used to identify scenarios likely to cause heat illness, based on the environmental conditions, and estimates of workload. However, as individuals respond differently to the same heat stress, it is often considered more appropriate to directly measure physiological responses (strain) so that behavioural changes may be used to reduce thermal strain. This project aimed to provide a theoretical basis for the development of a personal heat strain monitor, by evaluating a suitable surrogate index of core temperature for use in a working environment.

This index was an insulated skin temperature ($T_{skin\text{-}insul}$), located laterally to the T2-T4 spine. Using linear regression modelling, we have found this $T_{skin\text{-}insul}$ to closely approximate changes in oesophageal temperature ($T_{es}$). In this research, we applied these regression model to pre-existing data from our laboratory, resulting in 83% of the variance in $T_{es}$ being explained on the basis of $T_{skin\text{-}insul}$, with a standard error of the estimate of 0.15°C on individual trials. With multiple-linear regression analyses using physiological and psychophysical measures as potential predictor variables, the standard error of the estimate fell to 0.10°C. Due to variation in the intercept and slope values, no single prediction equation was able to be derived for all situations, and this technique was considered impractical for use in a commercial monitor.

By combining data collected at the same air temperature, four sets of equations were developed for each of three ambient temperature ranges. The predictor variables in these equations were: (i) $T_{skin\text{-}insul}$ only (simple linear regression modelling);
(ii) $T_{skin\text{-}insul}$ and heart rate; (iii) $T_{skin\text{-}insul}$, heart rate, mass and sum of six skinfolds; and (iv) perceived exertion, $T_{skin\text{-}insul}$, mass and sum of six skinfolds. It was possible to predict $T_{es}$ to an acceptable accuracy (standard error of estimate $<0.2$°C) using $T_{skin\text{-}insul}$, heart rate, body mass and sum of skinfolds in a multiple linear regression analysis.

When these equations were trialed on independent datasets (air temperature ≥30°C), all the equations developed for use in air temperatures of 30-36°C resulted in the standard error of the estimate being >0.2°C. The equations developed on data collected at 40°C had a similarly high error, with the most accurate equation, which utilised only $T_{skin-insul}$ as a predictor variable, having a standard error of the estimate of 0.05°C above the maximum recommended level. The prediction equations utilising additional variables recorded standard error of the estimate values exceeding twice the recommended maximum level.

These prediction equations were examined in relation to their efficacy for use with industrial heat strain guidelines. The equations developed using $T_{skin-insul}$, heart rate, mass and sum of six skinfolds were the most accurate equations at measuring a 0.8°C and 1.0°C change in $T_{es}$, at air temperatures of 30°C and 40°C. The prediction of an $T_{es}$ measurement of 38.0°C and 38.5°C revealed that equations using $T_{skin-insul}$ as the only predictor variable were most accurate. The equations for use at an air temperature of 36-40°C were considered sufficiently accurate for use in a personal monitoring system, with those developed for 30-36°C deemed to be unsuitable in the present form.

The prediction equations were trialed in two heat strain indices: the Physiological Strain Index and the Cumulative Heat Strain Index. The predicted $T_{es}$ measurement was inserted into these indices. It was found that the prediction equations using $T_{skin-insul}$ as the only predictor variable in the Physiological Strain Index, created a result that could be considered desirable in the air temperature range of 30-40°C. It was determined that, due to the level of inaccuracy of the equations, it was not possible to use surrogate measures of $T_{es}$ in the Cumulative Heat Strain Index. Future research should primarily focus on reducing $T_{skin-insul}$ measurement error, with the measurement then being trialed across a broad range of conditions to examine its efficacy for use in a personal monitoring system.

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## LIST OF COMMON ABBREVIATIONS

| | |
|---|---|
| CHSI | Cumulative Heat Strain Index |
| $f_c$ | Cardiac Frequency / Heart Rate |
| $f_{cmax}$ | Maximum cardiac frequency |
| IPE | Index of Physiological Effort |
| ISO | International Organisation for Standardisation |
| PSI | Physiological Strain Index |
| r | Correlation Coefficient |
| $r^2$ | Proportion of explained variability |
| RPE | Rating of Perceived Exertion |
| $S.E.E._y$ | Standard error of the estimate |
| $T_a$ | Air Temperature |
| $T_{es}$ | Oesophageal Temperature |
| $T_c$ | Core Temperature |
| $T_{re}$ | Rectal Temperature |
| $T_{skin\text{-}insul}$ | Insulated Skin Temperature |
| $T_{sk}$ | Skin Temperature |
| $\bar{T}_{sk}$ | Mean Skin Temperature |
| $\dot{V}_{02}$ | Oxygen Consumption |
| WBGT | Wet Bulb Globe Temperature |

# CHAPTER 1. INTRODUCTION

Maintaining thermal balance in a hot environment has proven to a problem for people working in industry and the defence forces (Ellis, 1977; Black, 1987; Bennett *et al.*, 1994; Bricknell, 1996; Kark *et al.*, 1996). Heat strain occurs when environmental factors (temperature, humidity, air movement) combine with metabolic heat production to place an uncompensable heat stress on the body. Numerous heat stress indices have been developed in an attempt to define the limits for human working conditions, and minimise the possibility of workers developing heat disorders. These are generally based on an assessment of prevailing climatic conditions, clothing and workload. The early warning signs of the onset of heat illness can be monitored using thermal strain indices such as body temperature, heart rate and sweat rate elevations. Monitoring of physiological variables will give an estimation of the heat strain an individual is experiencing and enable preventive measures to be taken in a timely manner, thus reducing the likelihood of developing a potentially fatal heat disorder. At the present time, there are difficulties in obtaining a deep body temperature measurement in the field due to the invasive level of most methods of monitoring deep body temperature. The primary focus of this project is to provide a theoretical basis upon which thermal strain monitoring may be based.

## 1.1 HEAT STRESS

The human, as a homeotherm, must maintain its core temperature ($T_c$) within 35-39°C to ensure survival. A delicate balance between heat gain and heat loss is required to ensure the body remains within this range. This balance may be represented by the heat balance equation:

$$S = M - (-W) \pm C \pm R - E \pm K \quad (W{\cdot}m^{-2})$$

**Equation 1.1**

*Where:*

$S$ = heat storage ($W{\cdot}m^{-2}$)

$M$ = metabolic heat production ($W{\cdot}m^{-2}$)

$W$ = work ($W{\cdot}m^{-2}$)

$C$ = heat exchange via convection ($W{\cdot}m^{-2}$)

$R$ = heat exchange via radiation ($W{\cdot}m^{-2}$)

$E$ = heat exchange via evaporation ($W{\cdot}m^{-2}$)

$K$ = heat exchange via conductance ($W{\cdot}m^{-2}$)

The heat balance equation quantifies the amount of heat stored within the body, and provides an indication of whether the body is in thermal equilibrium (Storage=0), is losing (Storage<0), or gaining heat (Storage>0). Three physiological mechanisms control the heat stored within the body: shivering, skin blood flow, and sweating. These mechanisms alter heat exchange through an increase in metabolic rate (shivering), and changing heat loss through convective and conductive (skin blood flow), and evaporative pathways (sweating).

The degree of thermal-exercise stress will dictate the physiological responses of the body. When the thermal-exercise stress is low-moderate, $T_c$ will increase, but can be maintained at this elevated level through the initiation of active vasodilation and sweating, and heat loss will equal heat production, representing compensable heat stress. When thermal-exercise stress is high, sweating and vasodilation eventually peak. If this is insufficient to dissipate excess heat, body temperature will rise uncompensably (Lind, 1963). It is during uncompensable heat stress that the body is at risk of developing hyperthermia. This project focusses upon uncompensable heat stress, and the development of a theoretical basis for a personal heat strain monitor which enables early recognition, and prevention of its occurrence through behaviour modification.

## 1.2 HEAT ILLNESS

Exposure to a hot environment, a high metabolic rate, or the combinations of both, may result in heat illness. Heat illness disorders range in severity from affecting skin function, fluid and electrolyte homeostasis, through to an impairment of temperature regulation, and may result in organ, system or whole body dysfunction (Table 1.1) (Shibolet *et al.*, 1976; Costrini *et al.*, 1979; Knochel, 1989). Furthermore, chronic exposure to heat may result in an increased susceptibility to heat illness, and affects general health and well being, with an increased incidence of various medical conditions reported (Leithead and Lind, 1964; Ellis, 1976; Ellis, 1977).

Heat stroke is the most serious of heat illnesses and it may be divided into two types; Classical Heat Stroke and Exertional Heat Stroke. Classical heat stroke occurs under sedentary conditions, and it most likely to occur in the elderly, frail or children exposed to a high heat load. Exertional heat stroke results from thermoregulatory overloading or failure during exercise in a warm environment. It typically affects healthy young and middle aged people (IUPS Thermal Commission, 2001). It is the aim of this project to prevent the development of exertional heat stroke by monitoring physiological strain during the activity, providing a level of awareness to the user that may result in a behavioural change to reduce heat strain.

### 1.2.1 Epidemiology of heat illness

To highlight the issue of heat illness, Table 1.2 summarises the epidemiology of heat illness across two occupations. Unfortunately, little statistical information is available concerning heat illnesses, and until recently, medical records in the military or industrial fields were not well maintained, thus resulting in an underestimation of the incidence of heat disorders. Heat illnesses have decreased considerably since the introduction of control measures in the late 1950's.

However to illustrate heat illness is still a concern, even with knowledge of managing heat stress and heat management techniques (such as fluid replacement and acclimatisation) in November 2004 it was reported that an Australian Soldier died

**Table 1.1:** Acute heat illnesses

| **Disorder** | **Symptoms** | **Aetiology/ Effect** |
|---|---|---|
| **Heat oedema** | Oedema of extremities, especially legs | Excessive vasodilation in skin |
| **Heat syncope** | Fainting, weakness, light headedness, nausea, loss of consciousness | Cardiac insufficiency, pooling of blood in veins. |
| **Heat cramp** | Muscular spasms- working muscles inc. abdominal muscles | Water/electrolyte imbalance |
| **Skin diseases** **Prickly heat, heat rash, anhidrosis** | Raised vesicles on skin, prickly heat on exposure to heat. Anhidrosis on affected areas | Prolonged sweating causes obstruction of the sweat glands, and subsequent reduction in sweating. |
| **Heat exhaustion** | Elevated core temperature, headache, nausea, cramps, fatigue, giddiness | Water / salt depletion |
| **Heat stroke** | Central nervous system dysfunction, core temperature $>40.5°C$ | Hyperthermia and potentially thermoregulatory failure |

**Table 1.2:** Epidemiology of heat illness in the mining industry and the defence forces

| **Occupational Group** | **Year** | **Morbidity rate** | **Mortality rate** | **Source** |
|---|---|---|---|---|
| **Miners** | 1931-1940 | | 19.3 per year | Wyndham, 1965 |
| | 1950 | | 0.041 per 1000 | Wyndham, 1965 |
| | 1956-61 | 7.33 per 1000 | 4.16 per 1000 | Wyndham, 1965 |
| **Defence Forces** | 1952-62 | 5.77 per 1000 | | Minard, 1967 |
| | 1955 | 1.27 per 1000 per week | | Minard, 1967 |
| | 1962 | 0.52 per 1000 per week | | Minard, 1967 |
| | 1982-1991 | 145 per year | | Kark, 1996 |

from heat related illness during a training exercise in Northern Tropical Australia, whilst another required hospitalisation from exertional heat stroke several days prior (Parry, 2004). Additionally, in 1998 a team of Polish mine rescue workers suffered heat stroke whilst completing a rescue (Personal Communication: P. Mackenzie-Woods, 2000[1]).

## 1.3 HEAT STRESS INDICES

There have been many attempts to quantify physiological strain. Most have been based on quantifying environmental stress (air temperature, radiant temperature, water vapour pressure, air velocity) and the impact of clothing and physical workload, in theoretical or laboratory situations. The greater emphasis on environmental stress rather than physiological strain is because these data are more easily obtainable. Furthermore, such indices were originally developed to predict stressful environments and to estimate working time prior to workers entering the environment (Wenzel, 1989). The focus of the current project is to evaluate the utility of these varied approaches, with the aim of providing a theoretical basis for prediction of heat strain.

Over the last 100 years many heat stress indices have been developed, some designed for specific environments and populations, others for general use. However there are many shortcomings with these indices, and particular problems faced by these indices include predicting strain at high temperatures and humidity, whilst wearing protective clothing, working at different intensities and the individuality of the response to the heat stress (Belding, 1970; Givoni, 1976; Lee, 1980; Mairaiux and Malchaire, 1995). The work of Wyndham (1974) identified the diverse range of rectal temperature responses that occurred in a group of miners following a five-hour exposure to a thermal-exercise stress (32°C wet bulb temperature, 1.0 litre·min$^{-1}$ oxygen consumption). After one-hour of exposure, the range of rectal temperature responses were normally distributed (Figure 1.1 A).

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[1] Paul Mackenzie-Wood. Manager Technology and Technical Services- Mines Rescue Service NSW

Plesae see print copy for Figure 1.1

**Figure 1.1:** Distribution of rectal temperature responses of 100 males after 1 (A) and 5 (B) hours of exercise (1.0 $l \cdot min^{-1}$) in a 32°C wet bulb environment. Adapted from Wyndham (1974).

Following five-hours of this thermal-exercise stress, the distribution was negatively skewed, with rectal temperatures of up to 39.8°C recorded (Figure 1.1 B). This illustrated the range of rectal temperature responses to the same thermal-exercise stress, and demonstrates the role of individual characteristics in the physiological response to a standard thermal-exercise stress.

Therefore, whilst heat stress indices are designed to protect the majority of workers, in many circumstances they have limited application to workers whose physiological responses are affected by factors not quantified within such stress indices: physical fitness, acclimation status, illness, body morphology, medication and drugs (Kenney, 1985). These variables vary between and within-individuals and make predicting physiological strain from stress very difficult. Therefore, several indices of strain utilising physiological indices have arisen, and these are the emphasis of the current project.

## 1.4 PHYSIOLOGICAL INDICES OF HEAT STRAIN

Heat stress indices can only attempt to predict average physiological strain. To ascertain actual strain, direct physiological monitoring is required. Heat strain manifests itself in several physiological variables, and the best indicators of this heat strain include: $T_c$, cardiac frequency ($f_c$), sweat rate, and skin temperature ($T_{sk}$).

### 1.4.1 Core temperature

Core temperature is commonly used as a criterion for the diagnosis of heat illness, and is indicative of heat storage within the body. The core of the body is represented by the central organs and surrounding tissues, and should remain within 35-39°C. The temperature of the outer tissue, the shell, can vary widely, and is strongly influenced by environmental conditions. The increase in $T_c$ observed during exercise is due to an increase in metabolic rate, is proportional to the relative exercise intensity, and is largely independent of ambient temperature (5-30°C) over a wide range of ambient conditions (Nielsen and Nielsen, 1962). The site from which to estimate $T_c$ remains somewhat controversial. However, the chosen site should exhibit several characteristics according to Cooper *et al.* (1964). First, it should be convenient, non invasive and painless. Second, it should not be influenced by local blood flow or environmental changes. Third, it should reflect quantitatively the changes of arterial blood temperature that influence thermoregulatory changes.

**1.4.1.1 Core temperature measurement**

Many sites are regularly used to measure $T_c$ in clinical and laboratory settings: oesophagus; gastro-intestinal tract; rectum; tympanic membrane; auditory canal; and mouth. Two of these measurements require further examination for this project: oesophageal temperature as it is the superior measurement of $T_c$ according to many criteria; and gastro-intestinal temperature because of its potential to be used in occupational settings.

It is suggested that the temperature of atrial blood is an appropriate approximation of $T_c$ as it approximates the temperature at the hypothalamus, a primary thermoregulatory centre. Oesophageal temperature closely approximates the temperature of blood in the pulmonary artery, and quickly responds to changes in $T_c$, and is therefore considered the best site for monitoring $T_c$ in clinical and laboratory environments (Shiraki *et al.*, 1986). It is however, an invasive measure that cannot be readily adapted for use in a working environment.

The gastro-intestinal pill has the potential to be used in field environments for the measurement of $T_c$. This method involves ingestion of a radio pill, which transmits the temperature from within the gastro-intestinal tract. The temperature varies between that of oesophageal and rectal temperature depending upon the location within the gastro-intestinal tract (O'Brien *et al.*, 1998). The reading may also be affected by strong radiant temperature, food and fluid intake, however a major drawback is the cost associated with this measurement (International Organization for Standardization, 1992).

#### 1.4.1.2 Surrogate indices of core temperature

Laboratory and clinical sites of $T_c$ measurement are not suitable for continual monitoring in the field. Therefore, alternate, or surrogate indexes of $T_c$ have been sought. Fox and Solman (1971) attempted to monitor $T_c$ (measured at the rectum, gastro-intestinal tract and auditory canal) from the skin surface by creating a region of zero heat flow, thus exteriorising $T_c$. This technique was found to work well in resting subjects and closely followed $T_c$ during fever, independently of $T_{sk}$. However, the level of accuracy was reduced in situations involving active subjects at high work rates (Fox *et al.*, 1973).

During anaesthesia commercially available liquid crystal forehead temperature strips have been used to gauge $T_c$ (Scholefield *et al.*, 1982; Vaughan *et al.*, 1982) These appear to have limited use, as demonstrated by very low correlations between $T_c$ and the liquid crystal strip measurement following anaesthesia, and the inability of the strips to correctly identify febrile patients (Scholefield *et al.*, 1982; Vaughan *et al.*, 1982).

More recently, an insulated skin temperature has been used as an index of $T_c$ by several groups (Bernard and Kenney, 1994; Bogh *et al.*, 1994; Taylor *et al.*, 1998). Taylor *et al.* (1998) found that insulated skin temperature was able to track oesophageal temperature during an incremental work-rest protocol, at air temperatures of 25-40°C, with a high correlation to oesophageal temperature ($r = 0.86$) This approach is less cumbersome than the zero gradient monitor, and is quite appropriate to use in the field.

### 1.4.2 Cardiac frequency

Cardiac frequency ($f_c$) is particularly responsive to changes in the thermal state of the body, and therefore may be considered a suitable candidate for use in a heat strain monitor. It is affected by metabolic stress, and the circulatory demands of the body during thermal stress (International Organization for Standardization, 1992). During thermal stress, the peripheral vasculature becomes dilated, and plasma volume decreases due to hypohydration. The combined effect of these changes is a reduction in stroke volume and to maintain cardiac output and subsequently mean arterial pressure during this stress, an increase in $f_c$ is required (Sawka and Wenger, 1988).

### 1.4.3 Sweat rate

Sweating is the primary avenue for heat loss at high ambient temperatures (Sawka and Wenger, 1988). Sweating increases as the thermal stress and $T_c$ increase, and as such, it has formed the basis from which several heat stress indices were derived. Sweat rate increases following acclimatisation, and may reach over 2 $l \cdot hr^{-1}$, causing significant hypohydration if exposed to this stress for an extended period without adequate fluid replacement (Sawka *et al.*, 1998). The physiological strain due to sweating places an additional load on the circulatory and thermoregulatory systems, and thus sweat rate may be an effective index from which heat strain may be monitored.

### 1.4.4 Skin temperature

Skin temperature is considered an index of thermal strain because it represents the result of the metabolic and environmental heat load, as well as the effectiveness of the skin blood flow and evaporative cooling (Belding, 1970). Furthermore, increased $T_{sk}$ will alter the thermal gradient between the air and the body, and can be used to indicate the ability of the body to lose heat. The convergence of $T_{sk}$ and $T_c$ is not considered a criterion for heat tolerance (Nunneley *et al.*, 1992; Taylor and Amos, 1997) however, the ability to lose heat is substantially reduced when the $T_c$ and $T_{sk}$ converge, and as such the measurement of $T_{sk}$ can be an indicator of physiological strain.

### 1.4.5 Psychophysical indices of thermal strain

Psychophysical indices of heat strain, such as ratings of perceived exertion, thermal sensation and thermal discomfort are regularly used in laboratory and field situations to ascertain the subjective feelings of physiological strain. These variables are strongly linked to physiological responses such as $f_c$, $T_{sk}$, skin wettedness, skin conductance and $T_c$ (Borg, 1962; Gagge *et al.*, 1967; Gagge *et al.*, 1969) and thus may provide a means of assessing heat strain.

## 1.5 HEAT STRAIN INDICES

There have been many indices developed that attempt to predict physiological strain to a given environmental and metabolic stimulus. However as discussed, the ability of these indices to predict thermal strain is questionable due to the unique nature of working environments and individuals' levels of heat tolerance. Thus, indices that include directly measured physiological responses have been sought. Just as heat stress indices use environmental and metabolic stimulus to quantify heat stress, physiological strain indices attempt to quantify the physiological strain of an individual, based on a combination of physiological measures.

Indices that have incorporated direct measurement of physiological responses include the Index of Physiological Effort (Robinson *et al.*, 1945) the Modified Craig Index (Hall and Polte, 1960), the Cumulative Heat Strain Index (Frank *et al.*, 2001), and the Physiological Strain Index (Moran *et al.*, 1998). Each of these indices rely on a combination of direct measurements of $T_c$, $T_{sk}$, sweat rate or $f_c$ to estimate thermal strain. This project is specifically interested in these direct measurements of physiological strain. Although these indices rely on direct measurements of $T_c$, if a substitute can be found, these indices may be incorporated into a heat strain monitor, to enable use in the field.

Physiological monitoring of a person during a thermal-exercise stress can provide an avenue for reducing the incidence of heat illness, whilst at the same time maximising the time that a worker can spend performing a task. The physiological strain experienced by an individual is unique and cannot be adequately determined using stress indices that do not allow for individual variation. Thus, the development of a personal heat strain monitor has important ramifications for workers in hot environments.

## 1.6 AIMS

The aim of the current project is develop a theoretical basis upon which a monitor of personal heat strain may be developed. The concept of using insulated skin temperature to approximate $T_c$ has been established in this laboratory, and although this method has limitations, this project aims to improve its use, and in conjunction with other physiological, psychophysiological or environmental variables, to develop the basis for a monitor of heat strain. This project will be undertaken in three parts.

### 1.6.1 Review of literature

A review of the heat stress/strain literature will aim to determine variables that may be utilised in a heat strain monitor, in addition to establishing the rationale behind a personal heat strain monitor. Includes a brief review of heat stress/strain indices.

### 1.6.2 Database analysis

A *post hoc* analysis of six databases will be used to ascertain which physiological, psychophysical and environmental variables can best predict physiological strain. The aim being to then use the most suitable variables to develop a basis for monitoring heat strain.

### 1.6.3 Index verification

Verification of the developed index will be completed using data not used in the development of the index. This verification process will also incorporate using the core temperature prediction equation, in published physiological strain indices.

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# CHAPTER 2: REVIEW OF HEAT STRESS AND HEAT STRAIN LITERATURE

## 2.1 INTRODUCTION

Environmental conditions are routinely measured in many industrial situations to gauge the heat stress a worker is placed under. Unfortunately, the way that an individual will respond to these conditions is dependant upon many factors, and cannot be ascertained merely by looking at the environmental stress or work being performed. Individual factors such as age, body composition, acclimatisation level, hydration, and aerobic fitness will alter the physiological response to a given stress stimulus (Kenney, 1985; Cheung and McLellan, 1998). In an environment where the incidence of heat illness is likely, monitoring the physiological responses of each individual worker is ideal to minimise the risk of a heat illness developing and maximise work productivity. It is currently impractical to monitor physiological strain in the workplace using existing methods, and this project will investigate the measurement of thermal strain using environmental, physiological and psychophysical measures separately or in combination.

## 2.2 INDICES OF PHYSIOLOGICAL STRAIN

Physiological strain during work in the heat is a multi-faceted phenomenon, and the strain experienced during this work may arise from various sources. These sources include: body heat storage; cardiovascular strain; and dehydration. Each of these factors are interlinked, and a change in one variable effects another factor in some way. Therefore, whilst many of these physiological indicators may stand alone as a useful indicator of strain, when they are combined, they may be able to provide a greater understanding of the physiological strain caused by a thermal-exercise stress. Figure 2.1 demonstrates how heat stress results in a physiological challenge to the body, and the consequences of such a challenge (Goldman, 1988). The point highlighted by this diagram is that the two means of losing heat (through an increase in skin blood flow, and sweating), are also the cause of heat illness under certain conditions. The increased skin blood flow results in less blood being returned

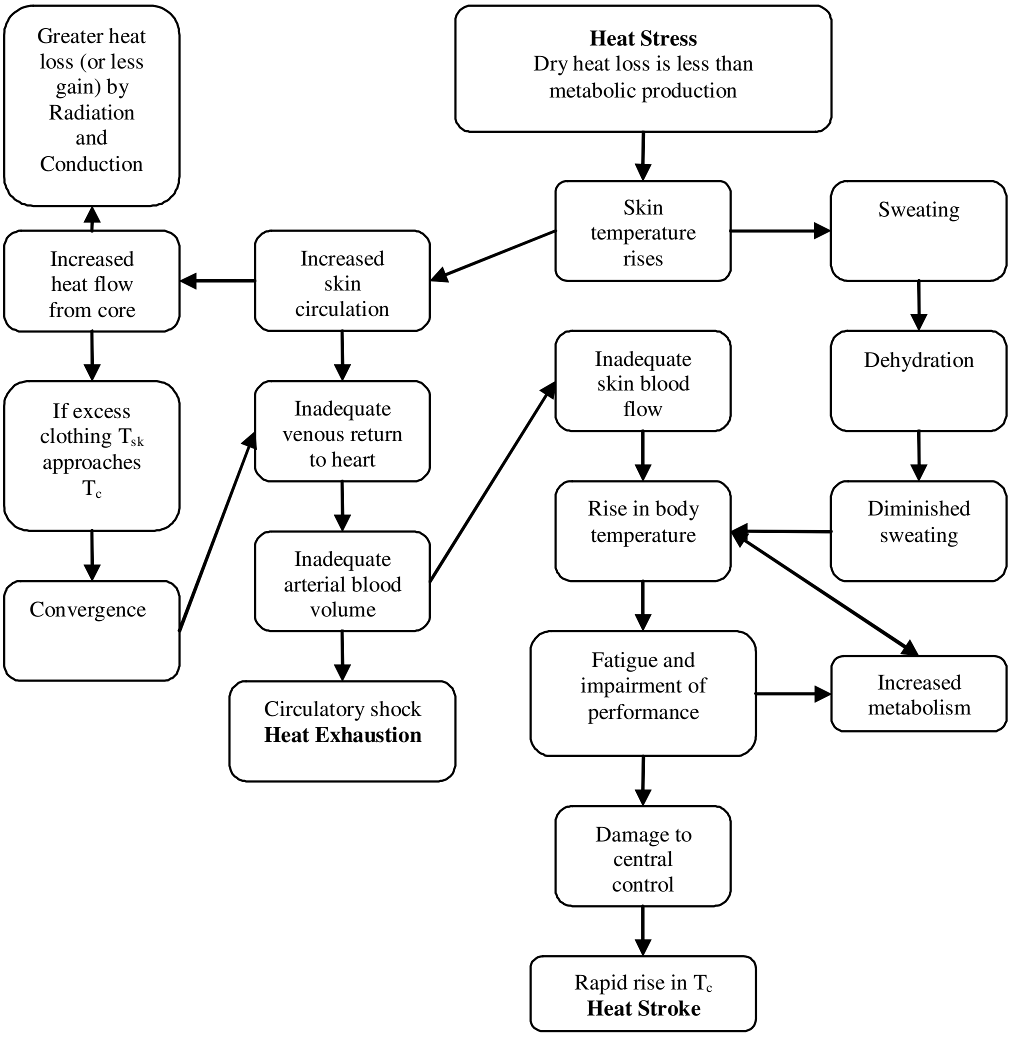


**Figure 2.1:** Role of heat stress in development of heat strain and illness. Adapted from Goldman (1998). Abbreviations: $T_{sk}$ = Skin temperature, $T_c$ = Core temperature, R= Radiation, C= Conduction

to the heart, and less blood being delivered to the brain and other organs, resulting in circulatory shock, where the sufferer will collapse. When sweating commences, the risk of dehydration increases if hydration is not maintained. Dehydration is a serious consequence since blood volume will be reduced, and the sweating response is reduced, exacerbating the effect of increased skin blood flow and resulting in a rise in body temperature. It is envisaged that several of these indices may be used in a personal heat strain monitor to enable continuous monitoring of workers in hot environments.

### 2.2.1 Core temperature

A continual increase of heat stored within the body during thermal-exercise stress results from an impeded ability to dissipate the heat produced within the body, and this is reflected as an increase in core temperature ($T_c$). Core temperature may be defined as the average temperature of the central tissues of the body, which should be maintained within the range 35-39°C. When a person is exposed to a hot environment, and is performing physical activity, $T_c$ will increase, but will plateau as a new thermal equilibrium is attained. This new steady state indicates that the heat stress is compensable. Within the ambient temperature ($T_a$) range of 5-30°C, the change in $T_c$ is largely independent of $T_a$, and is dependant upon the relative workload (Nielsen and Nielsen, 1962).Therefore, for a given workload, the change in $T_c$ observed will be greater in people with lower physical endurance.

When heat gain is greater than heat loss, heat storage will increase, and if it increases sufficiently, performance will decrease, the cardiovascular system is placed under further strain, and ultimately, health may be placed at risk (Gonzalez-Alonso *et al.*, 1997; Hales, 1997; Hancock and Vasmatzidis, 1998). An increase in $T_c$, is associated with physical and cognitive performance decrements. From a physiological perspective, hyperthermia may result in the development of heat exhaustion and heat stroke (Leithead and Lind, 1964), a potentially fatal heat illness. Furthermore, the increase in $T_c$, results in a reduction in cognitive performance, notably sustained attention (vigilance); increased reaction time; and disturbed spatial and time orientation (Hancock, 1986; Enander, 1989).

### 2.2.2 Cardiac frequency

Cardiac frequency ($f_c$) reflects the physiological strain placed upon the body by the environmental and metabolic demands. Many factors influence $f_c$, including the direct effect of increased $T_{c,}$ parasympathetic withdrawal, and sympathetic activation (Johnson and Proppe, 1996). Independent of metabolic demands, $f_c$ may increase by up to 36 beats·min$^{-1}$ for a 1°C change in $T_c$ (Haldane, 1905).

During thermal stress, heat must be moved from the core to the skin to dissipate the heat to the environment. This is accomplished by convection and conduction, and relies on an adequate cutaneous blood supply. Cutaneous blood flow can increase by increasing cardiac output or a redistribution of blood. Rowell (1974) suggested that, during mild and heavy exercise, cardiac output increases initially and is then maintained, primarily due to an increase in $f_c$, as stroke volume declines over the extended exercise period. During an exercise stress in a hot environment, a higher $f_c$ is seen at the same exercise intensity when compared to a cool environment (Rowell, 1974), indicating the increased physiological strain experienced in hot environments. Based on the available information, monitoring $f_c$ is an indicator of increasing physiological strain and may be of use in a personal heat strain monitor

### 2.2.3 Sweat rate

Sweating results in heat loss through evaporation, a key component of the heat balance equation (Equation 1.1). Evaporative heat loss is the predominant means for losing heat above 20°C, and when $T_a$ equals or exceeds $T_{sk}$ and dry heat loss is minimised or reversed, it is the primary means of losing heat (Sawka and Wenger, 1988).

Sweating provides a major challenge for fluid-electrolyte homeostasis, due to the substantial fluid deficits that may occur during a thermal-exercise stress. Hydration is usually inadequate, as sweat loss may exceed 2 l·hr$^{-1}$, and ingestion is typically below this, resulting in dehydration. Dehydration affects workers in several ways. First, the ability to perform work decreases as the level of dehydration increases (Goldman, 1988; Barr, 1999). Second, dehydration alters the sweating response resulting in a decline in sweat rate, consequently enhancing the risk of heat illness. Furthermore, dehydration results in a reduction of skin blood flow, facilitating the development of hyperthermia as the ability to exchange heat at the skin is reduced (Coyle, 1998). The control of sweating is very sensitive to changes in fluid balance, and during mild dehydration, a higher $T_c$ is required to elicit the same sweating response (Greenleaf and Castle, 1971; Nielsen *et al.*, 1971). Thus dehydration has many negative influences on thermoregulation, and the ability to predict sweat loss may be beneficial in a heat strain monitor.

Predicting sweat rate is difficult because the sweating response varies markedly within and between individuals and is affected by many factors. Aside from hydration, other factors influencing sweat rate include gender (Avellini *et al.*, 1980), acclimatisation level, habitual physical activity, skin wettedness, age, and sweat gland morphology (Sawka and Wenger, 1988).

In a working environment, mass change is the only way that sweat loss may be monitored. This method is only accurate if fluid intake and urine output are also known, and there is minimal absorption of the sweat by clothing. Within a laboratory, hygrometers used in conjunction with capsules attached to the skin may be used to determine sweat rate. A theoretical estimate of sweat rate from environmental conditions and metabolic demands using the predicted four-hour sweat rate heat stress index is also available. There are limitations with this index which will be discussed later in this review.

Sweat rate is regarded as a good predictor of physiological strain only when the heat stress is compensable (Mehta and Niyogi, 1970; Givoni, 1976), making this index useful only under these conditions. For the purpose of a monitor of heat strain, sweat rate manifests itself in the indices of $T_c$ and $f_c$. As sweat rate increases, the level of dehydration in a person will increase. This dehydration results in a reduction of plasma volume. To compensate for this loss of plasma volume, cardiac output must increase. Given that stroke volume declines with a loss in plasma volume, cardiac output can only be maintained by an increase in $f_c$. The reduction in plasma volume enhances the competition between the skin and core for blood. There will be less blood flowing to the skin for cooling, therefore heat exchange at the skin will decrease and $T_c$ will rise. Based on the physiological consequences of sweating, and the interaction of these with $T_c$, $f_c$ and $T_{sk}$, and the current absence of a technique for accurately measuring sweat rate in an occupational setting, there will be no further deliberation on the use of sweat rate for inclusion in a monitor of heat strain.

### 2.2.4 Skin temperature

The skin is the critical point at which heat exchange occurs. The temperature of the skin is primarily a function of ambient conditions (Saltin *et al.*, 1972) and the interaction of these conditions with the physiological responses of skin blood flow and sweat evaporation (Sawka and Wenger, 1988). According to Sawka and Wenger (1988), there are three justifications for measuring $T_{sk}$. First, for calculating heat storage within the body. Second, for calculating skin conductance and sensible heat exchange. Third, for determining the input of $T_{sk}$ into the thermoregulatory centre.

Whilst by itself $T_{sk}$ is not indicative of physiological strain, if it is considered in conjunction with $T_c$ or environmental temperature it may become an indicator of impending thermal-exercise strain. When the $T_a$ equals $T_{sk}$, no dry heat exchange is possible, making the body rely solely on evaporative heat loss to dissipate heat. A similar relationship exists between the $T_c$ and $T_{sk}$. When $T_{sk}$ converges with $T_c$, the ability to dissipate heat from the core to the skin is diminished (Pandolf and Goldman, 1978). As $T_c$ and $T_{sk}$ converge, there is also a compensatory increase in cutaneous blood flow. This results in further competition between the perfusion requirements of working muscle, and cutaneous flow for thermoregulation.

Early research suggested that the convergence of $T_c$ and $T_{sk}$ may be used as criteria for heat tolerance, and that when convergence occurred subject collapse was imminent (Pandolf and Goldman, 1978). However, further investigation (Nunneley *et al.*, 1992) revealed that convergence did not appear to be a criterion for heat tolerance, and there was evidence in previous research that revealed people continued to work, for up to 30 minutes following convergence of $T_{sk}$ and $T_c$, as measured by rectal temperature ($T_{re}$). Nevertheless, although convergence may not be an indicator of tolerance time, it does indicate substantial thermal strain, and that work will not be able to continue indefinitely, without a considerable level of hyperthermia being attained.

## 2.3 ENVIRONMENTAL, PHYSIOLOGICAL AND PSYCHOPHYSICAL MEASURES THAT MAY BE USED TO PREDICT PHYSIOLOGICAL STRAIN

The physiological measurements required for an accurate portrayal of physiological strain can only be accurately monitored in a laboratory. It is imperative however that workers in hot environments are aware of their current physiological state. To evaluate this physiological state, environmental, physiological and psychophysiological variables may be used to predict $T_c$, and other measures of physiological strain.

### 2.3.1 Environmental predictors

Environmental stresses are those that act on the body and disturb thermal homeostasis. Working in a hot environment poses several problems for workers: discomfort, loss of concentration and subsequent loss of productivity, development of unsafe working practices, heat disorders and heat illness, and interaction of the heat stress with other environmental hazards such as noise and carbon monoxide (Brotherhood, 1995). From a physiological perspective, the environmental conditions dictate the ability to lose heat from the body, and as such, monitoring environmental conditions may provide an insight into the physiological strain experienced by the
worker. There are four primary environmental variables that impact on heat exchange: $T_a$, humidity, radiant heat and air velocity. Santee and Gonzalez (1988)
provide an excellent review of the characteristics of the environment, and their relationship to heat exchange.

### 2.3.1.1 Ambient temperature

Ambient temperature (dry bulb), may be defined as the temperature of the surrounding medium (*eg*. air, water). The ability to lose heat by convection and conduction, is dependant upon the temperature gradient between the body and its surrounding medium. As this gradient decreases, the ability to lose heat to the surrounding medium declines. From a heat balance perspective, when $T_a$ approaches $T_{sk}$, the ability of the body to lose heat is minimised. When $T_a$ exceeds $T_{sk}$, the principles of heat transfer dictate that the body will gain heat from the environment, causing a rapid increase in heat storage.

### 2.3.1.2 Water vapour pressure

The water vapour pressure of the air plays a significant role in the ability of the body to evaporate sweat. As with temperature and the skin, the ability to evaporate sweat is dependant upon the water vapour gradient between the skin and air. When the water vapour pressure of the air is higher than that of the skin, the sweat cannot evaporate, and will drip from the body. If the sweat is not evaporated, no significant heat exchange will occur.

### 2.3.1.3 Radiation

The use of radiation in the heat balance equation relies upon the net effective radiation balance of an individual, which Santee and Gonzalez (1988) suggest comes from six sources, including solar, thermal, and from the individual. Thermal radiation is a key component of the heat balance equation (Equation 1.1), and is particularly important during outdoor work or in industries such as steelmaking.

### 2.3.1.4 Air velocity

Air velocity refers to the movement of air that an individual is in contact with. There are three ways in which air velocity is generated: forced air flow (such as from a fan); natural air flow; or air movement caused by bodily movement. Physiologically, air velocity plays a significant role in heat loss through convection and evaporation. As heat is transferred from the body to the air, the air at that point of the body warms up, a boundary layer is formed, and when this layer becomes a similar temperature to the body, no further dry heat exchange will occur. As the air velocity increases, this boundary layer changes more rapidly, and heat exchange is facilitated (Santee and Gonzalez, 1998).

## 2.3.2 Physiological variables

Physiological strain is a representation of the consequences of stress imposed by the environment and metabolism. As a person works, approximately 75% of the metabolic energy produced as heat. If this heat cannot be dissipated (due to circulatory insufficiency or environmental limitations) the $T_c$, $T_{sk}$, sweat rate and $f_c$ will all increase. With continual exposure to heat in a working environment maximal responses may be seen in the physiological responses, causing decreased work productivity, and exposing the worker to the risk of heat illness.

### 2.3.2.1 Core temperature

Many sites exist for $T_c$ measurement in clinical and laboratory use. These temperatures include oesophageal, rectal, gastro-intestinal, auditory canal, tympanic membrane, oral, axilla, bladder, urine, atrial, and brain (Cranston, 1954; Togawa, 1985; Shiraki *et al.*, 1986; Brinnel and Cabanac, 1989; International Organization for Standardization, 1992). The sites commonly used in a laboratory or field environment include rectum, auditory canal, oesophagus and gastro-intestinal tract. The other measurements are used in clinical or field environments, but are regarded as too invasive or difficult to obtain for regular use (*i.e.* atrial, brain and bladder), or the measurement is not as accurate as desired (*i.e.* axilla and oral). The ideal measurement of $T_c$ should be convenient, painless and comfortable, be unaffected by environmental temperatures, and reflect the arterial temperature that drives thermoregulatory responses (Cooper *et al.*, 1964).

#### *2.3.2.1.1 Oesophageal temperature*

Oesophageal temperature is regarded as the gold standard by most scientists for monitoring $T_c$ in the laboratory. It is measured using a thermocouple or thermistor, that is inserted through the nasal passage and down the oesophagus to a level corresponding to the level of the left ventricle. Oesophageal temperature responds rapidly to changes in blood temperature, with a lag of approximately 80 seconds with pulmonary artery temperature, and an average difference of 0.12°C with aortic temperature during hyperthermic therapy (Shiraki *et al.*, 1986). There is also a close relationship between $T_{es}$ and brain temperature (Eshel and Safar, 1999). The oesophagus has a rapid response time because of the close proximity to the heart and low heat capacity of the oesophagus (Sawka and Wenger, 1988).

*2.3.2.1.2 Rectal temperature*

Rectal temperature ($T_{re}$) is widely used because it is considered to be less invasive and minimally interferes with performance. The measurement requires insertion of a thermocouple or thermistor through the anal sphincter, to a depth greater than 10 cms (Sawka and Wenger, 1988). Nielsen and Nielsen (1962) found no difference in $T_{re}$ measurement using depths ranging from 12 - 27 cms from the anal sphincter.

Rectal temperature readings are generally higher than $T_{es}$ with Edwards *et al.* (1978) reporting a difference of 0.19°C at rest, and differences of 0.12-0.40°C are reported during steady state exercise (Nielsen and Nielsen, 1962; Edwards *et al.*, 1978). In febrile patients this difference between $T_{re}$ and right heart temperature was up to 0.8°C (Eichna *et al.*, 1951). Rectal temperature exhibits a lag and less variation when compared with $T_{es}$ during passive cooling and re-warming, as well as during exercise (Saltin *et al.*, 1970; Molnar and Read, 1974). Moran and Mendal (2002) highlighted this as the current method of choice for monitoring heat illness in a sporting population.

*2.3.2.1.3 Additional methods of monitoring core temperature*

Two measures of $T_c$ that have been commonly used in occupational settings are tympanic temperature and gastro-intestinal temperature. Tympanic temperature has been routinely used in the field as a predictor of $T_c$. The temperature varies around that of $T_{es}$ with Shiraki *et al.* (1986) reporting tympanic temperature being 0.2°C lower than $T_{es}$, and Brinnel and Cabanac (1989) reporting tympanic temperature as 0.1°C higher than $T_{es}$. Eglin and Tipton (2000) suggested that infrared tympanic temperature did not reflect $T_c$ in the field, as it measured 0.58°C ($\pm$0.60) lower than $T_{re}$. Infrared instruments are frequently used to measure $T_c$ in the field, but this technique allows only occasional monitoring, is subject to influence from $T_a$ and requires skilled personnel for accurate measurement (Hansen *et al.*, 1996), although recent advancements appear to have resolved some of the issues arising from use of tympanic temperature as a measurement of $T_c$ (Shibasaki *et al.*, 1998).

Gastro-intestinal temperature is suited for use in an occupational setting, and provides a temperature measurement that is similar to $T_{re}$ and $T_{es}$, depending upon the probe location within the gastro-intestinal tract (O'Brien *et al.*, 1998). Difficulties in retrieval of the probe, or the expense of the probes are required for consideration when using this measurement.

Although $T_c$ measurement in the field maybe difficult to obtain, it is perhaps the most critical index of physiological strain. A recent review by Moran and Mendal (2002) confirmed the difficulties faced in gaining an accurate measure of $T_c$ within the sporting environment to monitor heat illness. They concluded that based on the current methods available, monitoring of $T_{re}$ was considered the most appropriate for monitoring heat illness in sporting situations. This review did not consider alternate / surrogate indices of $T_c$ which have been developed, and these may be suited for use in a portable monitoring system. These will be discussed at length later in this review.

#### 2.3.2.2 Metabolic rate

The metabolic requirement of a task determines internal heat production. The body is approximately 20-25% efficient. Accordingly, for an external work rate of 200 Watts, 1000 Watts of energy are required, with the remaining 800 Watts appearing as heat, which requires dissipation to prevent storage. Hubbard (1979) demonstrated that the combination of exercise (an increase in metabolic rate) and external heat is collaborative in the development of exertional heat stroke.

In most situations, the metabolic rate is measured using indirect calorimetry. This method is not suitable during transient bursts of high intensity activity with a significant anaerobic component, however for the most part this can often be ignored (Gagge and Nishi, 1977). Measurement of metabolic rate requires expensive, and fragile equipment. Portable oxygen analysers are available, however these are large, cumbersome and impractical for prolonged use in a working environment. Equations are available for the prediction of metabolic rate for a wide range of activities, and these have the capacity to be incorporated into a heat strain monitor.

#### 2.3.2.3 Cardiac frequency

Cardiac frequency is regularly monitored in the field during many activities. Commercially available $f_c$ monitors are available at a low cost, and these are capable of storing data. It is a non-invasive and socially acceptable method of monitoring $f_c$. There are three ways in which $f_c$ may be monitored for assessment of workload: the actual $f_c$; the change in $f_c$; and the time taken for $f_c$ to return to a baseline or a nominated number (World Health Organisation, 1969). Monitoring $f_c$ may also play a role in the prediction of $T_c$, as illustrated by thermal cardiac reactivity, in which $f_c$ increases as $T_c$ increases, independent of the metabolic requirements.

#### 2.3.2.4 Skin temperature

The use of $T_{sk}$ in a heat strain monitor serves two purposes. First, the gradient between $T_{sk}$ and $T_a$, and $T_{sk}$ and $T_c$ may be used to indicate that the ability to lose heat to the environment is reduced, placing strain on the body, in particular at the point of convergence. Second, although $T_{sk}$ is strongly influenced by the ambient conditions, several methods of estimating $T_c$ from the intact surface have been developed. These methods are non-invasive, and have varying degrees of accuracy.

Skin temperature is usually measured using temperature sensors in contact with the skin, or with infrared temperature sensors. Skin temperature may be measured locally at single sites, or combined using a weighting system to determine mean $T_{sk}$. Use of a single site is useful for determining the biophysics of heat transfer, but a weighted mean $T_{sk}$ is most commonly used (Sawka and Wenger, 1988). Mean $T_{sk}$ is calculated using a weighted equation with four to 14 sites incorporated (Ramanathan, 1964; International Organization for Standardization, 1992). The use of $T_{sk}$ in a heat strain monitor is considered important, however measuring multiple sites is not feasible in an occupational setting. Skin temperature becomes more uniform in hotter environments, and therefore using a single site to measure $T_{sk}$ may be appropriate in a heat strain monitor, if this site is protected from radiant heat (Goldman, 1988). The thigh was suggested as the site of choice in a personal monitoring system developed by Cassels (1991).

There are three non-invasive techniques of measuring $T_c$ which have been derived using $T_{sk}$. This approach is more socially acceptable than using direct $T_c$ measures, and potentially more suitable for use in a working population. These three methods are: insulated skin temperature ($T_{skin\text{-}insul}$); zero gradient thermometers; and liquid crystal strips.

*2.3.2.4.1 Insulated skin temperature*

The use of $T_{skin\text{-}insul}$ as a surrogate, or substitute, $T_c$ has been studied extensively (Bogh *et al.*, 1994; Taylor and Amos, 1997). Insulated skin temperature is measured in a similar technique to $T_{sk}$, using a skin thermistor, however it is insulated from the environment by a highly insulative material. This technique has been shown to track oesophageal temperature during a work rest protocol with a high correlation (r), but also a high standard error of the estimate ($S.E.E._y$), with a correlation of 0.83 and $S.E.E._y$ = 1.28°C reported, over a wide range of ambient conditions (25-40°C). If $T_a$ is known, the prediction of $T_{sk}$ from $T_{skin\text{-}insul}$ can be improved ($S.E.E._y$ = 0.37-0.45°C), as $T_a$ is known to change the slope and intercept between $T_{es}$ and $T_{skin\text{-}insul}$ (Taylor *et al.*, 1998). Bernard and Kenney (1994) used a system that passively measured heat flux from the skin using an insulated disk temperature. This disk temperature had a high correlation with $T_{re}$ (r=0.93, *S.E.E.*$_y$=0.2°C), under conditions of high heat stress. The relationship between $T_{re}$ and disk temperature was altered by clothing (single layer clothing compared to vapour barrier clothing).

The matter of the best site to measure $T_{skin\text{-}insul}$ was addressed by Taylor and colleagues (1998). A comparison of four sites: wrist, forehead, jugular and spine, revealed that the location on the spine (just off the spine at the level of T2-T4) showed the most promise, as it had the highest consistent correlation with $T_{es}$ and, from a practical perspective, may prove to be the most suitable. Other sites that have been used include the midaxilla / chest (Bernard and Kenney, 1994) and the abdomen (Eglin and Tipton, 2000). Eglin and Tipton (2000) reported that the relationship between $T_{skin\text{-}insul}$ and $T_c$ was very good within a given exposure and exercise, but the correlation between exposures and exercise (within the same individual), and different individuals was poor. They found that the site used by Taylor *et al.* (1998) at the level of T2 did not reflect gastro-intestinal temperature or $T_{re}$ (r=-0.34, 0.02 and 0.61 across three subjects). Instead, the temperature recorded on the abdomen that was embedded in the thermal monitoring system showed a better relationship with gastro-intestinal temperature (r =0.95 ±0.02) and $T_{re}$ (r = 0.97 ±0.04).

*2.3.2.4.2 Zero gradient thermometer*

The zero gradient thermometer, has also been used to predict $T_c$ from the intact skin surface (Fox and Solman, 1971; Fox *et al.*, 1973). Using a heated pad, a region of zero heat flow is created, with the temperature of the heating pad being adjusted by thermal gradients between a temperature sensor on the skin surface and, within layers of insulation. As $T_c$ changes, this heat is transferred to the skin surface, thus exteriorising $T_c$. This method of determining $T_c$ was initially shown to be relatively reliable during anaesthesia, and the measurement was independent of $T_{sk}$ (Fox *et al.*, 1973). Further examination of the relationship between the deep body temperature monitor and $T_c$ revealed the relationship became poor when exercise was performed and when $T_{sk}$ changed rapidly (Fox *et al.*, 1973; Muravchick, 1983). This variation was further exaggerated during exercise in cooler climates (Fox *et al.*, 1973).

*2.3.2.4.3 Liquid crystal strips*

Liquid crystal strips have been developed and used for estimating $T_c$ in clinical and home use. These commercially-available strips are usually placed on the forehead, and change colour or give a reading according to the predicted $T_c$. The forehead has been shown to provide a better estimate of $T_c$ than that of the neck, as the core-forehead gradient exceeded 0.5°C only one-third of the time during the induction of anaesthesia and changes in $T_a$, compared to approximately half the time with the neck-core gradient (Ikeda *et al.*, 1997). The validity of these strips was questionable in the detection of febrile patients, or in post-operative patients (Scholefield *et al.*, 1982; Vaughan *et al.*, 1982).

## 2.3.3 Psychophysical indices of strain

### 2.3.3.1 Thermal sensation

Thermal sensation is a psychophysical phenomenon associated with an individual's perception of the temperature of their body. Physiologically, thermal sensation is strongly related to $T_a$ and $T_{sk}$, but it is not as strongly associated with core or muscle temperature, or metabolic rate (Gagge *et al.*, 1969).

### 2.3.3.2 Thermal comfort

Thermal comfort has been studied extensively for many years, in particular by heating and ventilation engineers concerned with air conditioning within buildings. The studies by Houghten and Yagloglou (1923 a,b) attempted to determine combinations of temperature and humidity that produced equivalent feelings of comfort (effective temperature index). This study formed the basis for many heat stress indices that are used today (Yaglou and Minard, 1957).

Thermal comfort is associated with an absence of sweating, and conversely, discomfort is associated with sweating and skin wettedness (a function of sweat secretion, air movement and humidity). Discomfort is not related to $T_a$ or $T_{sk}$, however the upper limit of comfort was associated with a skin wettedness level of 50-65%, and an exercise intensity of up to 50% of maximum oxygen uptake (Gagge *et al.*, 1969). The close relationship that exists between thermal comfort, metabolic rate, $T_c$ and skin wettedness may be useful to aid in the prediction of $T_c$.

#### 2.3.3.3 Perceived exertion

Perceived exertion is defined as the subjective intensity of effort, strain, or discomfort that is experienced during exercise (Robertson *et al.*, 1986). Borg (1998) further noted that perceived exertion is related to exercise intensity, and is adjusted according to motivation, emotion and pathological conditions, yet is also dependant on somatic symptoms and sensory cues. Perceived exertion may be divided into central and local perceived exertion, which enables differentiation between local muscular fatigue and central fatigue (Ekblom and Goldbarg, 1971).

During firefighting and emergency work in the heat, Gamberale and Holmer (1975) found that Rating of Perceived Exertion (RPE) continued to track $f_c$ responses, but the RPE was lower than the one-to-ten relationship usually observed when the 15 point scale is used, and maximal $f_c$ responses were observed at an RPE of 14. Similarly, during a cycling protocol in normal and hot conditions, a marked increase in $f_c$ was observed, without a corresponding change in perceived exertion. These findings are supported by Maw *et al* (1993) who also found that for a given RPE in the heat, $f_c$ was 10-14 beats·min$^{-1}$ higher than in a neutral climate. The change in $f_c$ observed by Gamberale and Holmer (1975) was attributed to a change in heat storage within the body, and not a factor of increased workload. Similar findings were reported by Pandolf (1975), who suggested that $f_c$ is not the major factor in the subjective perception of exercise, and that as a single physiological variable it cannot be used to predict perceived exertion.

The use of perceived exertion in a heat strain monitor may be useful because it is combines physiological and psychological feelings of perceived exertion. It is simple to administer, and as such may prove very useful in a monitor of heat strain, not only in potentially assisting predict some physiological variables, but as an indicator in itself, providing a cognitive dimension, not previously considered in personal monitoring.

### 2.3.4 Additional factors affecting heat strain

#### 2.3.4.1 Clothing

Clothing affects the ability to exchange heat and alters the effect of the environment on heat exchange. Increasing clothing insulation may allow less heat to enter, but also does not allow adequate evaporation. From the perspective of the heat balance equation, clothing decreases radiative and convective heat transfer, and the removal of heat by minimising evaporative heat loss (Vogt *et al.*, 1981). Protective clothing has been shown to increase cardiorespiratory and thermal strain significantly during sub-maximal work (Ilmarinen *et al.*, 1994; Louhevaara *et al.*, 1995; Smith *et al.*, 1996), reduce maximal power output (Louhevaara *et al.*, 1995), and reduce the $T_c$ at which exhaustion occurs (Montain *et al.*, 1994). More recently Fogarty (2002) reported that exercise time during recumbent cycling in a 40°C environment was reduced from 58.9 min (±3.8) to 52.5 min (±4.1) when a fire-fighter turnout uniform was worn compared to a control condition (shorts).

The insulative capacity of clothing is measured in a unit known as the clo. One clo is equivalent to the insulation provided by the equivalent of a business suit. Many heat stress indices incorporate clothing levels into their equations. The wet bulb globe temperature (WBGT) index is commonly used in many hot industries to define the working conditions for the workers. In its current form, this index is not suitable for use with protective clothing (National Institute of Occupational Safety and Health, 1986), and further adjustments are necessary to enable prediction of a safe working environment for workers wearing this clothing. It has been estimated that these adjustments to the WBGT temperature may need to be in the vicinity of 11°C to protect workers in fully encapsulating clothing ensembles such as the nuclear biological and chemical clothing ensembles (Kenney, 1987; Paull and Rosenthal, 1987). Nuclear biological and chemical protective clothing is impermeable to vapour, thus sweat will have minimal chance to evaporate. Therefore monitoring workers in this clothing is essential, and ambient conditions both within the suit and outside of the suit have an impact on heat exchange. Face masks have also been shown to limit facial heat exchange, and cause an increase in $M_{sw}$, $f_c$ and $T_{sk}$ (Martin and Callaway, 1974).

#### 2.3.4.2 Exposure time

The longer the time that an individual is exposed to a hot environment when performing high-intensity work, the greater is the risk of developing heat illness. Knowing the exposure time of a worker to an environment is critical for determining the physiological strain that will result following exposure to an environment. Exposure to a hot environment for a short time may produce no ill effects, yet long-term exposure may result in development of hyperthermia. A review of the effects of heat on task performance by Ramsey (1995) found that as exposure time increased, performance in perceptual tasks suffered significant decrements that were not evident earlier during the heat exposure.

Time is an important factor to use in a heat strain monitor. As Bernard and Kenney (1994) discuss, the time that an individual is at a given heat exposure, or $f_c$ is important, and the use of time weighted averages may be appropriate. A high $f_c$ for one minute may be perfectly safe, but over an extended period is indicative of increasing physiological strain. Thus, the limits set on a heat strain monitor may need to be based on a time weighted average, similar to those equations of Bernard and Kenney, utilising the measurement of time within a monitor.

## 2.4 OVERVIEW OF HEAT STRESS AND STRAIN INDICES

Many different indices have been developed to predict environmental stress or physiological strain. These can be categorised predominantly into two types: (1) heat stress indices, which monitor environmental conditions; and (2) physiological strain indices, which monitor or predict physiological responses and performance.

### 2.4.1 Indices of heat stress

For more than 95 years, the physiological responses to given environmental conditions have been studied, and indices based on these responses and conditions have been developed. For a heat stress index to be acceptable for use in industry it should address five key areas (Dukes-Dobos and Henschel, 1973). First, use of the index must be proven in practice. Second, the physiological-relevant factors must be measured (*i.e.* $T_a$, radiant temperature, air speed, humidity, metabolic rate). Third, the measurements and calculations required should be simple and not require complex physiological monitoring. Fourth, the exposure limits expressed by the index should reflect the magnitude of human response. Fifth, it should be applicable for a wide range of working conditions. Many excellent reviews are available describing the development and criticisms of many heat stress indices (Belding, 1970; Kerslake, 1972; Lee, 1980; Goldman, 1988) and it is not the purpose of this chapter to repeat these. Relevant information pertaining to these indices is presented in discussion.

Heat stress indices were developed in two principal ways. Empirical indices were based on ascertaining the environmental conditions that produced a given physiological response under laboratory conditions. Rational indices were theoretically based on heat transfer coefficients that determine equivalent conditions that allow equal levels of heat transfer. Each index has a set of environmental conditions that it proposes cause the same level of heat stress. For example, it is proposed that 28°C, 95% humidity causes the same level of heat stress as 44°C, 10% humidity using the WBGT index (Yaglou and Minard, 1957) or 28°C, 10% humidity using the predicted 4-hr sweat rate ($P_4SR$) index. To allow comparisons of heat stress indices, lines of equivalent levels of heat stress (according to the heat stress index) may be presented on a psychometric chart.

Wenzel (1978) used this method to compare eight different heat stress indices. Based on a reference value of 28°C, 100% humidity lines were drawn on a psychometric chart corresponding to the same value of heat stress at different environmental conditions. When a dry environment (10% relative humidity) was compared to the heat stress at 100% humidity, the $T_a$ corresponding to the same level of heat stress varied between heat stress indices by almost 19.5°C (Figure 2.2). Therefore, Wenzel explains that it is impossible to definitively answer the question of which dry bulb temperature at 10% humidity would correspond to the same level of heat stress as is encountered at 28°C, 100% humidity, as the answer depends entirely on the heat stress index is used.

Wenzel (1973) also investigated the relationship between heat stress indices and actual physiological responses. To do this, he compared the relationship between the lines of equivalent heat stress (according to each heat strain index), with lines of equivalent physiological responses (mean equivalence lines) based on the $f_c$ and $T_c$ responses of three subjects over three workloads and in a variety of environmental conditions. It may be interpreted that an accurate heat stress index should follow the mean equivalence lines of physiological responses, that is, equivalent physiological responses that have been plotted on a psychrometric chart.

Using environmental conditions that are commonly found in underground mines as a reference temperature (28°C, 100% humidity), Wenzel (1978) plotted the equivalent temperatures derived from six common heat stress indices on a psychrometric chart, and compared these with the mean equivalence lines. The equivalent temperatures are those in which each index would predict to be at the same level of heat stress. The further from the mean equivalence lines that the lines of equivalent temperatures fell, the greater the discrepancy between the physiological responses and the imposed stress. This illustrated that those indices derived from empirical studies of actual physiological responses in a high level of heat stress (such as Robinson, 1945) were superior. Indices such as the WBGT (Yaglou and Minard, 1957), perhaps the most widely used heat stress index, were poor at predicting heat strain (Figure 2.3).

**Figure 2.2**: Equivalent combinations of ambient temperature and air humidity for eight heat stress indices

Abbreviations: P4SR = Predicted 4-hr sweat rate; IPE = Index of physiological

Please see print copy for figure 2.2

effort; ITS = Index of thermal stress; BET = Basic effective temperature; HSI = Heat stress index; WBGT = Wet bulb globe temperature index; TAR = Thermal acceptance ratio; WB = Psychrometric wet-bulb temperature. Redrawn and adapted from Wenzel (1973).

Please see print copy for Figure 2.3

**Figure 2.3:** Comparison of lines of equivalent physiological strain (dashed) with lines of equivalent wet bulb globe temperature (straight). Redrawn and adapted from Wenzel (1973).

An important point to consider for the WBGT index, is that it was initially derived from the effective temperature index, developed by Houghten and Yaglogou (1923a,b). This index was primarily a comfort-based index, as the psychophysical measurement of thermal comfort was the primary variable considered.

The strengths of heat stress indices lie in their ability to give an indication of the thermal stress prior to entering the environment, enabling exposure limits to be derived both for individuals and a large number of workers. However there are many drawbacks with these indices. Some indices assume a constant $T_{sk}$, yet $T_{sk}$ is not constant, nor homogenous over the entire body. During work or thermal stress, particularly in vapour barrier clothing, $T_{sk}$ often rises well above 35-36°C, the assumed $T_{sk}$ for these indices (Shvartz and Benor, 1972; Pandolf and Goldman, 1978; Nunneley *et al.*, 1992). Recently, local $T_{sk}$ was measured at over 50°C in firefighters during training exercises (Eglin and Tipton, 2000). The large variability observed in $T_{sk}$ has significant implications for heat exchange of the body since the gradient from the core to skin is reduced, and reversed, decreasing the ability of the body to reduce heat. Furthermore, heat stress indices only consider environmental conditions. In vapour barrier clothing, the ambient conditions will only have a limited impact on heat exchange, and the conditions within the garment are more critical. Studies of workers in the South African gold mines (Wyndham, 1974) found that a group of workers exposed to the same heat stress demonstrated large differences in $T_{re}$. These differences were exacerbated over longer heat exposures and illustrate that factors other than the level of heat stress determine heat strain. Many individual factors affect the physiological responses of a worker in a hot environment (Kenney, 1985). These may be chronic (*i.e.* age and body composition) or acute (*i.e.* medication, a lack of sleep and alcohol consumption). Furthermore, individual characteristics that affect heat stress vary according to the type of stress (Havenith *et al.*, 1998). To combine all of these variables into an easy to use index, applicable and accurate to all workers in a variety of environments has not yet been performed. With so many variables that interact to influence heat strain, the monitoring of actual physiological strain may prove to be more valuable than monitoring the stress variables.

### 2.4.2 Indices of physiological strain

An index of physiological strain uses physiological measurements to evaluate the strain of an individual. These indices use $f_c$, $T_c$, $T_{sk}$ and sweat loss/rate to predict heat strain. In general, these indices compare the current level of each strain measurement with baseline measurements, and a maximal measurement derived from recommended guidelines or individual observations of the subjects. There have been four primary indices developed: Robinson's Index of Physiological Effort (IPE) (Robinson *et al.*, 1945); the modified Craig index ($I_s$) (Hall and Polte, 1960); the Cumulative Heat Strain Index (CHSI) (Frank *et al.*, 1996); and the Physiological Strain Index (PSI)(Moran, Shitzer and Pandolf, 1998).

#### 2.4.2.1 The Index of Physiological Effort

The IPE was originally developed as a heat stress index, but within this development, a physiological strain index was also developed.

$$E_p = E_h + E_s + E_r + E_w$$

**Equation 2.1**

$$Eh = \frac{100}{H_2 - H_1}(H_3 - H_1)$$

**Equation 2.1 a**

$$Es = \frac{100}{S_2 - S_1}(S_3 - S_1)$$

**Equation 2.1 b**

$$Er = \frac{100}{R_2 - R_1}(R_3 - R_1)$$

**Equation 2.1 c**

$$Ew = \frac{100}{W_2 - W_1}(W_3 - W_1)$$

**Equation 2.1 d**

Where:

$E_p$ = the index of physiological effort.

$E_h$, $E_s$ $E_r$, and $E_w$ = the effects of the environment on heart rate, skin temperature, rectal temperature and sweating respectively.

$H_1$, $S_1$, $R_1$, and $W_1$ = the base values of heart rate, skin temperature, rectal temperature, and sweating respectively.

$H_2$, $S_2$, $R_2$ and $W_2$ = the maximal values observed during exposure to the most extreme environments for heart rate, skin temperature, rectal temperature, and sweating respectively.

$H_3$, $S_3$, $R_3$ and $W_3$ = the current observations for heart rate, skin temperature, rectal temperature, and sweating respectively.

This index may use recommended guidelines as the values for the maximal values observed during exposure to the most extreme environment ($H_2$, $S_2$, $R_2$ *and* $W_2$), and use the actual values obtained during the heat exposure and rest for the base and current values of the physiological measurements ($H_1$, *S1*, $R_1$, $W_1$ $H_3$, $S_3$, $R_3$ and $W_3$). A major criticism of this index is that it considers each of the variables to contribute equally to strain, for example, $T_{sk}$ has equal importance as $T_c$. There are several other criticisms of the IPE as a heat stress index (the number of subjects it was developed on, lack of an adjustment for radiant heat, and its suitability for acclimatised individuals only) however these are not relevant to the use of the IPE as an index of physiological strain for monitoring purposes. The use of sweat rate as an indicator of physiological strain limits the use of this index in the field.

#### 2.4.2.2 The modified Craig index of physiological strain

This index has been used as a comparative index in studies comparing the physiological strain experienced using different cooling methods (Kissen, Summers, Buehring, Alexander and Smedley, 1976; Kissen, Alexander, Smedley, Buehring, Ward, and Lowe, 1976; Webbon *et al.*, 1978) and different clothing ensembles (Kaufman, 1988). The index allows comparison amongst different conditions at the end of exposures, and during the exposures.

To determine the strain during an exposure repeated mass measurements are required to determine sweat production. Determination of sweat rate in industrial environments is difficult because a large amount of sweat may be absorbed by the clothing, and therefore under predicting the amount of sweat produced. This limits the use of this index in practical situations. The standardisation of the core and sweat responses to an hourly rate enables a comparison to be made of exposures differing in time. This index assumes that a 1.0°C change in $T_{re}$ (per hour), a $f_c$ of 100 and 1.0 kg sweat loss (per hour) are equal contributors to the rating of overall physiological strain. This method may overestimate the role of $f_c$ in strain, since a $f_c$ of 50 is equivalent to 0.5 kg of sweat loss and 0.5°C change in $T_c$. It may be more appropriate to modify the use of $f_c$ in this equation, and express it as a change, similar to the use of $T_c$ and sweat rate.

$I_s = (HR/100) + \Delta T_r + \Delta_{wn}$

**Equation 2.2**

Where: $I_s$ = index of strain

HR = terminal heart rate

$\Delta T_r$ = rise in rectal temperature (°C·hr$^{-1}$)

$\Delta W_n$ = sweat production (nude weight loss, kg·hr$^{-1}$)

### 2.4.2.3 Physiological Strain Index

The PSI was developed by Moran and colleagues (1998), and as illustrated in Equation 2.3, relies on direct measurements of $T_{re}$ and $f_c$. The index will return a number from zero to ten providing the measurements do not exceed 39.5°C or 180 beats·min$^{-1}$ or fall below baseline values. Further research validated this index in the assessment of gender differences and hydration state (Moran, Montain and Pandolf, 1998; Moran *et al.*, 1999). A PSI value greater than ten may be achieved if either, or both $f_c$ and $T_{re}$, are above 39.5°C for $T_{re}$ or $f_c$ is more than 180 beats·min$^{-1}$. Furthermore, a number of less than 0 may be attained if measurements fall below the baseline values set. There is an equal ranking of $T_{re}$ and $f_c$, with each given a value out of five.

This index does not show cumulative strain, and it is hypothesised that cumulative strain will be evidenced by increased $T_{re}$ and $f_c$, and these values not returning to baseline immediately after the cessation of exercise. The index shows an increase and a reduction in physiological strain with a reduction in either $T_{re}$ or $f_c$. The effect of ageing on maximal $f_c$ is not taken into consideration with the PSI. Maximal $f_c$ ($f_{cmax}$) is predicted using the equation $f_{cmax} = 220$ -age, and therefore the limit imposed in the PSI is equivalent to the $f_{cmax}$ of a 40 year-old. If adjustments are made to the upper limit for $f_c$ to account for aging, only small differences in the PSI are found according to Moran *et al*. (2002) but add to the complexity of using the index.

$$PSI = 5(T_{ret} - T_{re0}) \cdot (39.5 - T_{re0})^{-1} + 5(HR_t - HR_0) \cdot (180 - HR_0)^{-1} \qquad \textbf{Equation 2.3}$$

Where*:*

$T_{ret}$ and $HR_t$ = simultaneous measurements of rectal temperature ($T_{re}$°C) and heart rate (HR beats·min$^{-1}$) taken at any time

$T_{re0}$ and $HR_0$ = baseline values of $T_{re}$ and HR

#### 2.4.2.4 Cumulative Heat Strain Index

The cumulative heat strain index (Frank *et al.*, 1996; 2001) is based on the measurements of heart beats and $T_{re}$ (Equation 2.4). The index is based on the close linked relationship between $f_c$ and $T_c$, they should be considered as a combined entity, not as two separate entities, as suggested within other physiological strain indices. The CHSI multiplies the change in $T_{re}$ (as indicated by area under the curve) with the number of heart beats counted (cumulative heart rate) to give an indication of the "physiological cost" of the exposure. The level of strain is indicated by the size of the number (arbitrary units), and comparisons of strain levels are only possible between exposures of the same duration. Using the combination of $T_{re}$ or $f_c$, the CHSI was able to differentiate the thermal strain experienced whilst wearing two types of protective clothing where no significant difference existed in end point $T_{re}$ or $f_c$ (Frank *et al.*, 2001). The measurement of heart beats instead of $f_c$ poses difficulties that can be overcome with equipment modification, however it is a more complex index.

**Equation 2.4** $$CHSI = \left[ \sum_{o}^{t} hb - HR_0 \cdot t \right] 10^{-3} \cdot \left[ \int_{0}^{t} Tr \cdot dt - Tr_0 \cdot t \right]$$

*Where*:

CHSI = cumulative heat strain index

hb = heart beats

$HR_0$ = initial-lowest heart rate (beats per minute$^{-1}$)

$T_{re}$ = rectal temperature (°C)

$T_{re0}$ = rectal temperature at baseline (°C)

t = time (min) from the onset of measurements

**2.4.2.5 Comparison of heat strain indices**

The four heat strain indices described above all rely on physiological measurements. The ability to measure $T_c$, $f_c$, $T_{sk}$ and sweat rate in an applied setting have been mentioned earlier. Currently this limits the use of these indices in an applied setting, in particular the IPE and Modified Craig Index as they require the measurement of sweat rate. A technique for measuring sweat rate in an applied setting, that would be suitable for use in these indices is not yet available, and therefore limits the application of these indices in the field. Use of $T_c$ within these equations limits the practical use of these indices. The gastrointestinal pill has been incorporated as a measure of $T_c$ during field-based trials and was able to be incorporated successfully into the PSI (Cotter *et al.*, 2000). Methods of indirectly measuring $T_c$, such as $T_{skin\text{-}insul}$, may be suitable for incorporation into these indices provided they can accurately depict $T_c$ (personal communication K. Pandolf, 2000).

Each of the indices described is not without its criticisms. The PSI does not account for age-related changes, as it assumes a maximum $f_c$ of 180. Given the age-related decline of maximum $f_c$, it is a fair assumption to assume that a 50-year-old is under greater physiological strain at a $f_c$ of 150, than a 20-year-old. This difference would not be reflected in the PSI, yet is an important factor to take into consideration if $f_c$ is to be used as an indicator of heat strain. This criticism also applies to the CHSI, as an older individual at the same level of the CHSI is under greater strain than a younger person. The PSI and IPE have the capacity to set upper limits for each physiological variable within the equation. This is not possible with the CHSI and Modified Craig Index. At present, the PSI is considered the most suitable index to use in a heat strain monitor provided a valid method of measuring $T_c$ is available.

### 2.4.3 Heat strain predictive modelling

In 1972, Givoni and Goldman incorporated metabolic heat load, environmental heat load, and the level of evaporative cooling into an equation to predict $T_{re}$. This equation incorporates many factors into determining the above variables including clothing characteristics, terrain and speed information, anthropometric variables and environmental conditions. Improvements to this model incorporated individual characteristics (maximal oxygen uptake, gender, acclimation status and hydration status) were made by (Pandolf *et al.*, 1986). This prediction equation developed by the United States Army Research Institute of Environmental Medicine was shown to be appropriate for use with pre- and post- acclimatised subjects wearing protective clothing (Gonzalez *et al.*, 1997) Limitations of this model noted by Gonzalez and colleagues (1997) were the limited range on environmental conditions that the model had been validated over, and the conservative nature of the index whereby fit and acclimatised subjects exceeded the tolerance times and predicted $T_c$ without adverse effects. There tended to be an over prediction of $T_{re}$ made by these indices and suggested that this model did not closely predict $T_c$ over the three hour heat exposure (Cadarette *et al.*, 1999). Adaptations to the original model resulted in a less dramatic increase in predicted $T_{re}$ at the start of exercise and improved the accuracy of the equation across all conditions. The revised model predicted tolerance times of subjects in 66% of the experimental conditions. These models still require further validation and additional input of other characteristic to improve the accuracy of the predictions.

Other prediction equations were developed to predict sweating (Shapiro *et al.*, 1982) and $f_c$ (Givoni and Goldman, 1973) and require input of environmental conditions, metabolic rate and clothing. Recently Havenith (2001) developed a model of thermoregulation incorporating individual variables. Havenith (2001) added body mass, fat, acclimatisation status, body surface area and maximal oxygen uptake to the model, which already incorporated environmental variables, clothing characteristics and activity to predict $T_c$ and $T_{sk}$, with the effect of these changes determined by the available literature. Across a range of conditions the new model incorporating the individual characteristics improved the correlation with $T_{re}$ from 0.36 to 0.63, with the best relationship observed in a warm/humid environment (using relative workload, r = 0.67) and hot/dry environment (using absolute workload, r=0.65). The poorest relationship was observed in a cold environment (r=-0.09). The mean error was reduced from -0.25°C to -0.08°C.

## 2.5 RECOMMENDED PHYSIOLOGICAL LIMITS FOR WORKING ENVIRONMENTS

The World Health Organisation in 1969 outlined a recommendation that under normal working circumstances, $T_c$ should not exceed 38.0°C for prolonged daily exposures in heavy working conditions. Should $T_c$ be continually monitored through $T_{re}$, it was considered that work should be allowed to continue until a $T_{re}$ of up to 39°C was attained, should there be no other signs and symptoms limiting work. The ISO (1992) detailed this recommended temperature further, noting that a change in $T_c$ of 1°C or a $T_c$ of 38°C should be the limiting factor under the following conditions: $T_c$ is measured only on an intermittent basis; Auditory canal or tympanic temperature is the measurement site; there are no competent medical personnel available; or no other physiological measurements are available. If the heat storage is rapid, and $T_{re}$ or intra-abdominal temperature measurement is used, the criteria are the same as these sites have low thermal inertia and are slow to change.

A $T_c$ of 38.5°C was considered appropriate to use as a threshold if the following conditions applied: $T_c$ is measured continually at the oesophagus; there has been medically screening and acclimatisation has been effective; other physiological measurements, notably $f_c$ are available; and the exposure can be stopped at any time when signs or symptoms of heat stress result, or the worker can leave at any time. The article concludes that $T_c$ should never arise above 39.0°C.

The ISO (1992) also make recommendation for the maximum changes in $f_c$ that should be observed in a working environment. In environments where heavy physiological strain is expected, the ISO suggest that in conjunction with $T_c$ measurement the following guidelines apply: $f_c$ should not exceed less than an individuals maximum heart rate less 20 $b \cdot min^{-1}$. Ideally, maximal $f_c$ will have been determined through testing rather than using theoretical predictions which can vary by 20 $b \cdot min^{-1}$. It is recommended that the increase in $f_c$, from thermal origin (*i.e.* not from physical activity) should not exceed 60 $b \cdot min^{-1}$.

The National Institute of Safety and Health (NIOSH) released guidelines in 1986 for the change in heart rate, during recovery as a way of monitoring physiological strain. In this method, heart rate is recorded for a 3-min period from the cessation of work, and the measures recorded between 30-sec and 1-min ($P_1$) and 2-min 30-sec and 3-min ($P_3$) be used to gauge the thermal strain. If the P3 measurement is less than 90 $beats \cdot min^{-1}$, the work is considered sustainable and not at risk of developing heat strain. If the P3 measurement is approximately 90 $beats \cdot min^{-1}$, and the difference between P1 and P3 is approximately 10 $beats \cdot min^{-1}$, then the physiological strain is high, but heat storage is unlikely or is minimal. Should the P3 value exceed 90 $beats \cdot min^{-1}$, and the difference between P1 and P3 be less than 10 $beats \cdot min^{-1}$, it is considered that the physiological strain is high and work should be modified.

## 2.6 SUMMARY

A wealth of research has been completed in the area of environmental physiology and the impact of heat stress on physiological strain, and it is impossible, nor necessary to summarise all of it for the purpose of this literature review. It is critical to note that for over 100 years attempts have been made to predict the relationship between environmental conditions and physiological strain, resulting in numerous heat stress indices. However, what is unknown is the quantitative role of individual factors in predicting the physiological response to heat strain. Thus, personal monitoring of physiological strain is considered critical for people who are going to be placed in uncompensable or unpredictable environmental conditions, to prevent heat illness.

Physiological strain is evidenced by changes in many physiological measures including $T_c$, $T_{sk}$, $f_c$ and sweat rate. Deep body temperature is one of the best variables to consider in a heat strain monitor as it both affects the other physiological measures, and is in turn affected by the response of these systems. It is a critical measure of heat strain and whilst there are many accurate methods for monitoring this within a laboratory, there are limited techniques acceptable for use in a working population. Thus, a method of predicting deep body temperature, that is suitable and acceptable for use in an industrial setting, is critical for preventing heat related illnesses. One such method that may be considered suitable is the use of an insulated skin temperature measurement such as that used by Taylor *et al.* (1998) and similar to that of Bernard and Kenney (1994). The development of such a tool may then be used in conjunction with physiological strain indices, such as the physiological strain index, to give a relative estimate of the physiological strain in comparison with recommended strain guidelines. This project will identify the suitability for this measure to be incorporated into a personal monitoring system

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# CHAPTER 3. PREDICTION OF BODY CORE TEMPERATURE

Core temperature ($T_c$) is a key indicator of physiological strain, as it is a consequence and measure of body heat storage. Oesophageal temperature ($T_{es}$) is regarded as the benchmark for non-invasive laboratory measurement of $T_c$, since it closely approximates right atrial blood temperature, the temperature of the blood that flows directly to the hypothalamus (Cooper and Kenyon, 1957). As such, it is also considered the best measure of heat strain.

However, it is impractical to use $T_{es}$ as a measure of $T_c$ in the field, and therefore, the development of a surrogate index of $T_c$ to use in a heat strain monitor for field use is considered crucial. Previous work from this laboratory ascertained that appropriately measured insulated skin temperatures ($T_{skin\text{-}insul}$) from several sites have a high correlation with $T_{es}$, across warm-hot conditions, and may be suitable as a surrogate index of $T_{es}$ (Taylor *et al.*, 1998). Figure 3.1 demonstrates the relationship between $T_{es}$ and $T_{skin\text{-}isul}$ during two trials conducted with different protocols and in different air temperatures ($T_a$). It may be noted that in each case, although the offset varied markedly, in each trial the $T_{skin\text{-}insul}$ measurement was shown to closely track the changes in $T_{es}$. Of note is the rapid rise in both measures near the conclusion of each trial, and the attainment of steady state in Figure 3.1A. The aim of this chapter was therefore to further evaluate a suitable surrogate index of $T_{es}$. A valid index of $T_c$ that could be measured under working conditions, would enable personal physiological monitoring of this measure.

It is envisaged that the model developed has the capacity to be built into a personal heat strain monitor, and with the potential measurement of other physiological strain indices, can give an indication of the individual's response to heat stress and enable them to make behavioural changes to prevent the development of heat illness. This heat strain monitor may then be enhanced by using the $T_{es}$ prediction model, with validated heat strain indices to give an overall rating of the heat strain being experienced. In a practical sense, a heat strain monitor could allow workers in high

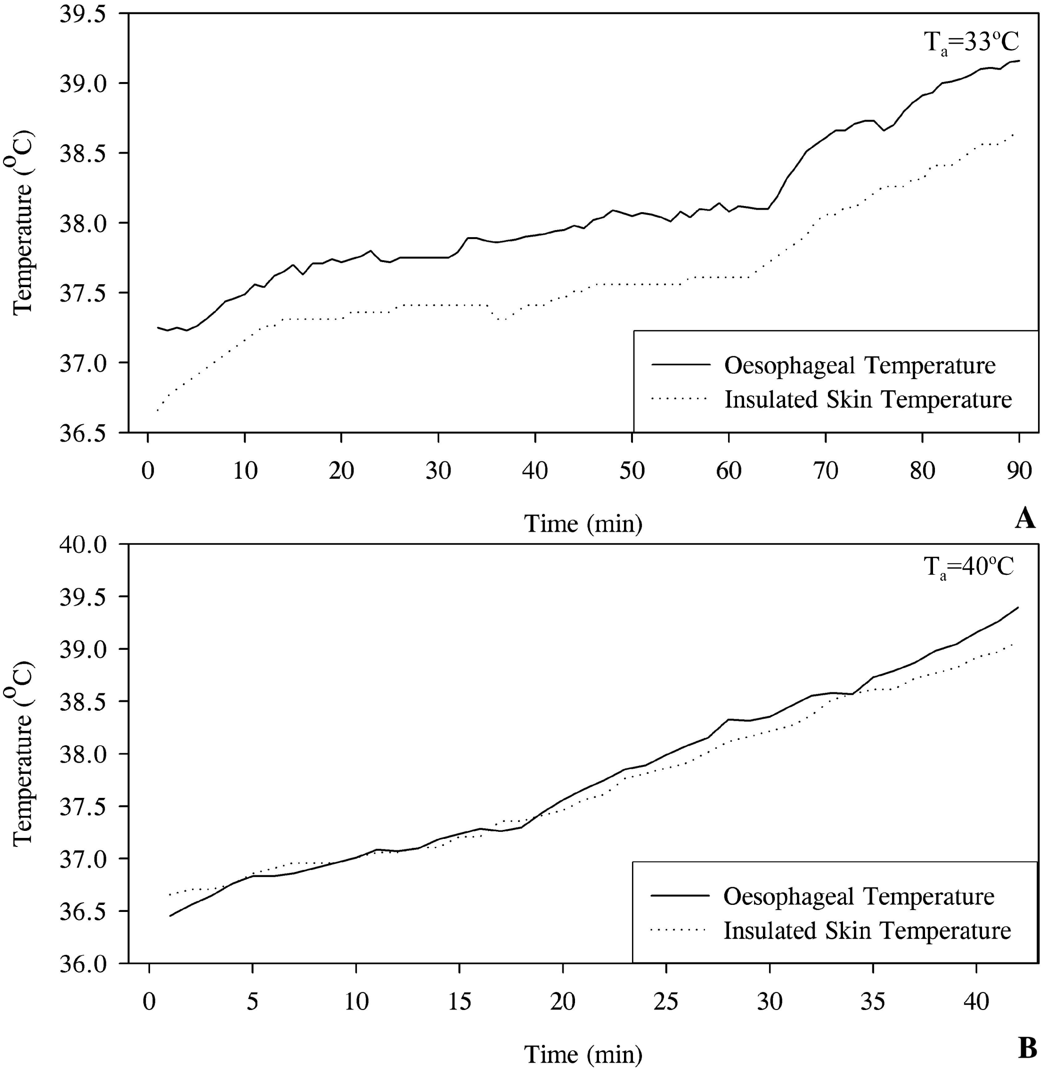


**Figure 3.1:** Relationship between oesophageal temperature and insulated skin temperature during two trials. A: A 90-min incremental exercise protocol with no rest periods conducted at an air temperature of 33°C. B: A work-rest protocol to volitional fatigue conducted at an air temperature of 40°C. $T_a$= Air temperature.

risk environments such as fire fighters, mines rescue workers and defence personnel to be aware of their current $T_{c.}$

Therefore, this chapter will continue the investigation into whether $T_{skin\text{-}insul}$, a modified skin temperature, in conjunction with other physiological and psychophysical variables, may be used as a surrogate index of $T_{es}$ in a personal heat strain monitor. Theses analyses were performed using linear regression modelling, on previously collected data from this laboratory and were examined in five groups of analyses:

- Prediction of heat strain within individual trials

The purpose of these analyses was to examine the ability of $T_{skin\text{-}insul}$ and other variables (physical and psychophysical) to predict $T_{es}$ within trials. The accuracy of this technique, and any similarities in models were identified.

- Influence of rest on the predictive ability within individual trials

The purpose of these analyses was to assess if the relationship between the predictor variables and $T_{es}$ was altered by rest or exercise by separating these components. This differed from the previous analyses where the data had been combined, and was used to assess if a more accurate model may be developed for use during the critical exercise period.

- Prediction of $T_{es}$ within research studies

The purpose of the within-study analyses was to identify if a more practical prediction model could be developed (than those developed in the analyses above) using data from trials collected within the same study and air temperature. The results of the univariate and multivariate analyses were reviewed and compared in relation to suggested standards.

- Accuracy of different techniques in the prediction of $T_{es}$

The purpose of this analysis was to assess if predicting the change in $T_{es}$ was more accurate than predicting the actual $T_{es}$. The visual observation of data suggested many similarities in the slope of the data, but that the intercept varied widely.

- Prediction of $T_{es}$ across studies

The purpose of these analyses was to use data from a range of conditions to generate a prediction model that could be applied to a less specific situation, and more applicable to what may be encountered outside a clinical setting. Thus all data collected at the same $T_a$ (which was shown to be a major variable impacting on the relationship between $T_{skin\text{-}insul}$ and $T_{es}$) was combined for these analyses. These analyses were used to formulate the final prediction equations (four models) for three $T_a$ ranges which were trialed on independent data to assess their efficacy (Chapter 4).

## 3.1 CHARACTERISTICS OF DATA AND STATISTICAL METHODS

Data from three research studies were used in the prediction of $T_{es}$ (Wilsmore, 1997; Taylor *et al.*, 1998; Armstrong and Fogarty, 1999) and represented 64 experimental trials. The environmental conditions, exercise mode and clothing varied between research studies (Table 3.1). Studies were selected which recorded the following measures: $T_{es}$, $T_{skin\text{-}insul}$ and cardiac frequency ($f_c$). The complete list of other relevant variables measured during the studies may be found in Table 3.1. Each study was sub-divided into the experimental trials conducted at the same $T_a$, providing six studies for examination (refer to Table 3.1 for the reference number allocated to each study).

The first phase of these analyses involved removing erroneous data to ensure that only valid physiological measurements were used. In determining whether or not erroneous data were present, visual observation of each measurement was required. Observations that led to the conclusion that these data were inaccurate and should be discarded included:

(a) When $T_{skin\text{-}insul}$ decreased, whilst $T_{es}$ and local $T_{sk}$ (as measured at the scapula), increased indicating that the thermistor may have lost skin contact;

(b) Data that showed irregularities in $T_{es}$ such as a depression after consuming water

**Table 3.1:** Research study characteristics and text reference

| Research Study | Study | Database | $T_a$ (°C) | Exercise mode | Clothing | Number of trials analysed | Mean trial length (min) | Measurements collected |
|---|---|---|---|---|---|---|---|---|
| **Taylor *et al.* (1998)** | I | 1 | 25 | Treadmill | DPCU | 7 | 96.1 | Subject characteristics, environmental conditions, $T_{es}$ $T_{re}$, $T_{sk}$, $T_{skin\text{-}insul}$, $f_c$. Sweat loss, RPE, TS, TD, Work rate |
| | III | 2 | 33 | | | 6 | 102.0 | |
| | V | 3 | 40 | | | 6 | 89.2 | |
| **Wilsmore (1997)** | II | 1 | 27 | Recumbent cycling | Shorts and shoes | 12 | 90 | Subject characteristics, environmental conditions, $T_{es}$ $T_{re}$, $T_{sk}$, $T_{skin\text{-}insul}$, $f_c$, Sweat loss, RPE, TS, TD, Work rate |
| | VI | 3 | 40 | | | 17 | 90 | |
| **Armstrong / Fogarty (1999)** | IV | 2 | 33 | Cycling | DPCU | 5 | 91.8 | Subject characteristics, environmental conditions, $T_{es}$, $T_{re}$, $T_{skin\text{-}insul}$, $T_{top}$ $f_c$, Sweat loss, RPE, Work rate |

Note: Mean trial length includes exercise time only. Study refers to number allocated to study for text reference. Database refers to data from studies combined together. Abbreviations: $T_a$ = Air temperature at which the data were collected. DPCU = Disruptive Pattern Combat Uniform, $T_{es}$ = Oesophageal temperature, $T_{re}$ = Rectal temperature, $T_{sk}$ = Skin temperature (8 sites), $T_{skin\text{-}insul}$ = Insulated Skin temperature, $f_c$ = heart rate, RPE - Rating of Perceived Exertion, TS = Thermal Sensation, TD = Thermal Discomfort.

were not used in the analyses, as they did not indicate a valid physiological measurement; and

(c) A change in $T_{es}$ that did not follow the trend observed in other measures of $T_c$ (rectal temperature and /or auditory canal temperature) and $T_{sk}$ as it may have indicated movement of the temperature probe, or that kinking of the probe during insertion resulted in the reading being influenced by air movement during breathing.

Elimination of these data reduced the amount of data available for analysis, but ensured that data used to predict $T_c$ were based on valid physiological responses. Fifty-three experimental trials were available for the final analyses after removal of trials where significant errors were present.

Based on the literature review (Chapter 2) and available data, the following variables were selected as being most relevant in the initial analysis: $T_{skin\text{-}insul}$ (Figure 3.2); $f_c$ ($b \cdot min^{-1}$); mean skin temperature ($\bar{T}_{sk}$, °C); work rate (Watts); and psychophysical measures (rating of perceived exertion (RPE), thermal sensation (TS) and thermal discomfort (TD). However, not all variables were sampled within each study (Table 3.1).

All continuously measured variables were recorded at intervals ranging from 5-15 sec. The psychophysical measures were recorded at 5-17 min intervals. Work rate was derived directly from the ergometer setting, or in the case of the treadmill, calculated using the following first principles equation:

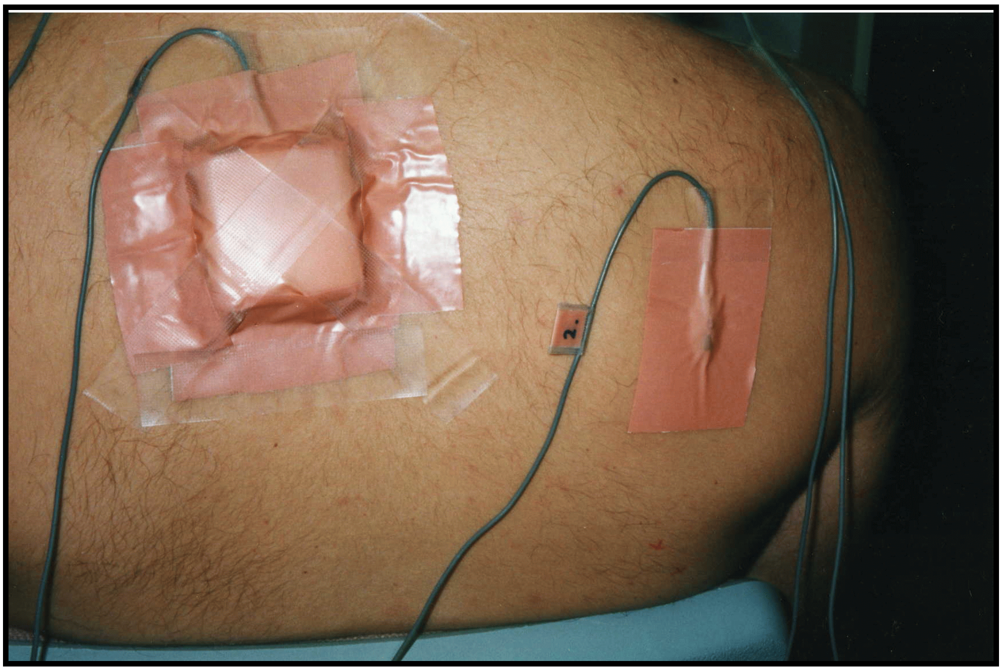

**Figure 3.2:** Photograph of insulated skin temperature (left). The thermistor is covered by a 0.5 x 3.0 x 3.0 cm piece of closed-cell foam, and a small wad of cotton wool. This is secured to the scapula (adjacent to spine, at the level of T2-T4) with waterproof tape. Non-insulated ski temperature is shown on the right.

Work rate (Watts) = (exercising $\dot{V}_{02}$- resting $\dot{V}_{02}$) * 1000 * 20.192 / 4 / 60 * 1000

**Equation 3.1**

*Where*:

$\dot{V}o_2$ = oxygen consumption ($l \cdot min^{-1}$)

1000 = conversion of $litres \cdot min^{-1}$ to $ml \cdot min^{-1}$

20.192 = the thermal equivalent of $O_2$ for the non-protein respiratory quotient ($J \cdot l^{-1}$) of 0.9

4 = efficiency of the exercise (25%)

60 = converts from hours to minutes

Exercising oxygen consumption ($\dot{V}_{02}$) on the treadmill was approximated from the following equations (American College of Sports Medicine, 1995),with resting $\dot{V}_{02}$ defined as 3.5 ml·kg·min:

For speeds of 50-100 $m \cdot min^{-1}$ :

$\dot{V}_{02}$=3.5 $ml \cdot kg^{-1} \cdot min^{-1}$ + $m \cdot min^{-1}$ * 0.1 + grade (fraction) * $m \cdot min^{-1}$ * 1.8

**Equation 3.2**

For speed >100 $m \cdot min^{-1}$:

$\dot{V}_{02}$= 3.5 $ml \cdot kg^{-1} \cdot min^{-1}$ + $m \cdot min^{-1}$ * 0.2 + grade (fraction) * $m \cdot min^{-1}$ * 0.9

**Equation 3.3**

### 3.1.1 Methods of analysis

The analysis of interval and continuous data consisted of two steps. First, the relationship between $T_{skin-insul}$ and $T_{es}$ was analysed for each trial using simple linear regression, based on Equation 3.4 (BMDP Statistical Software, Inc, Los Angeles, CA, USA).

$$\hat{Y} = bX + a$$

**Equation 3.4**

Where:

$\hat{Y}$ = predicted value of variable

$b$ = the slope of the regression line

$X$ = the predictor variable

$\alpha$ = the intercept

Second, forward stepping, multiple linear regression analysis, using the least squares method, was completed on each individual trial (Equation 3.5) using the variables indicated in Table 3.2 as potential predictor variables.

$$\hat{Y} = b_o + b_1 X_1 + b_2 X_2 + \ldots + b_p X_p$$

**Equation 3.5**

Where:

$\hat{Y}$ = predicted value of variable
$b_o$ = intercept
$b_1$, $b_2$ and $b_p$ = the regression coefficients for the predictor variables
$X_1$, $X_2$ and $X_p$ = the predictor variables

Entry of any variable into the regression equation was based on the *F* statistic and tolerance level. The model parameters were set as: *F* to *enter* = 4.00; *F* to *remove* = 3.99; and tolerance = 0.001. The *F* to enter and *F* to remove values were calculated from Equation 3.6 and 3.7.

$$F \text{ to enter} = [RSS_{(p)} - RSS_{(p+1)}]/[RSS_{(p+1)}/N-p-2)]$$ **Equation 3.6**

$$F \text{ to remove} = [RSS_{(p-1)} - RSS_{(p)}]/[RSS_{(p)}/(N-p-1)]$$ **Equation 3.7**

*Where:*

$RSS_{(p)}$ = residual sum of squares with *p* variables in the model

Within the equation, if the *F* value was lower than the *F* to *remove* value, the variable was removed from the equation. These parameters allowed only variables that contributed significantly to improving the equation to be incorporated within the $T_{es}$ prediction equation, with the *F* to enter value corresponding to a *p* value of 0.10.

Two predominant regression statistics were considered across all analyses to ascertain the accuracy of the equation: the correlation squared value ($r^2$); and the standard error of the estimate ($S.E.E._y$). The correlation squared value is the Pearson correlation statistic squared, and gives the proportion of variance in $T_{es}$ that can be explained by the regression model. The $S.E.E._y$ is the standard deviation of the error, indicating the amount that the predicted scores vary around the measured score, and is calculated as the square root of the residual mean square.

The decision for determining an acceptable $S.E.E._y$ was based on calculating the error that would be considered acceptable by industry from a performance perspective, and from a physiological perspective as industry requires that, with safety in mind, productivity must also be maximised. Within Chapter Two, the acceptable physiological limits were outlined, and it was proposed by Bernard and Kenney (1994) that a $T_c$ of 38.5°C would be considered permissible with continual monitoring. Thus, it was determined that a $S.E.E._y$ of 0.2°C was considered an acceptable prediction error, since this would ensure that the measured $T_{es}$ was within 0.4°C of the actual $T_{es}$ 95% of the time. It would also be predicted with 68% certainty that within the predicted $T_{es}$ range of 38.1-38.9°C, the actual $T_{es}$ would be between 38.3-38.7°C.

## 3.2 PREDICTION OF OESOPHAGEAL TEMPERATURE

### <u>3.2.1 Analysis of individual trials</u>

#### 3.2.1.1 Role of psychophysical variables

Each experimental trial was examined in two analyses as a continuous[2] and interval dataset[3] (Table 3.2). The analysis of the regression models examined three factors:

1. The proportion of variance in $T_{es}$ accounted for by $T_{skin\text{-}insul}$ alone, and the $S.E.E._y$ of these predictions, using the continuous and interval data sets.
2. The $S.E.E._y$ and proportion of variance in $T_{es}$ explained after multiple linear regression analysis was performed on the continuous and interval

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[2]Continuous data refers to data that was collected on at least 1-min frequency, or could be calculated for each minute of the trial

[3]Interval data refers to data that was collected at pre-determined intervals during the trial, and was at a frequency of less than 1-min. Data points used in the analysis corresponded to the same intervals as the collection of the psychophysical data (every 5-17min according to study design).

**Table 3.2:** Analysis of individual trials

| | **Measurements available for inclusion in analysis** | |
|---|---|---|
| **Analysis** | **Simple Linear Regression Analysis** | **Multiple Linear Regression Analysis** |
| **Interval** data points used in analysis corresponded to time that the psychohphysical measurements were recorded | Insulated skin temperature | Insulated skin temperature, Heart rate, Mean skin temperature#, Work rate (watts), Temperature on top of insulation*, Perceived Exertion (whole body), Perceived Exertion (chest), Perceived Exertion (legs), Thermal Discomfort#, Thermal Sensation# |
| **Continuous** | Insulated skin temperature | Insulated skin temperature, Heart rate, Mean skin temperature#, Work rate (watts), Temperature on top of insulation* |

# denotes data not available for inclusion in the database: Armstrong and Fogarty 1999

* denotes data only available for inclusion in the database: Armstrong and Fogarty 1999

data using all available variables outlined in Table 3.2.

3. Determination of which method (continuous or interval) explained more variance in the prediction of $T_{es}$, and had a lower $S.E.E._y$ (paired two-tailed t-test).

#### 3.2.1.2 Results and discussion

The regression equations for each individual trial are contained in Appendix A, and the regression statistics for the simple and multiple linear regression analyses are summarised by study in Figures 3.3A and B. The principle observations were:

1. The ability to predict $T_{es}$ within an individual trial using $T_{skin\text{-}insul}$ as the sole predictor variable was considered high in both interval and continuous datasets. Across all studies, an average of over 80% of the proportion of the variance in $T_{es}$ could be explained by the prediction models, with the mean value of only one study falling below this level (Study I). The $r^2$ and $S.E.E._y$ values indicated that the interval and continuous datasets were significantly different ($p<0.01$). Both attained a high level of accuracy with the mean values of the $S.E.E._y$ being lower than the maximum recommended value of 0.2°C (represented by the light, continuous, and darker, interval, grey bars on the left side of each study, Figure 3.3A and B). The high level of accuracy in the individual univariate analyses suggests that $T_{skin\text{-}insul}$ may be a suitable surrogate for $T_{es}$ in a working population, and may form the basis for prediction modelling in a commercial monitor.
2. Utilising additional predictor variables in a multivariate analysis significantly increased the proportion of variance accounted for within the continuous and interval analyses with an average of 0.91 and 0.92 respectively ($p<0.05$), and the mean $S.E.E._y$ values were lower than the maximum required level of 0.2°C. Neither the $r^2$ or $S.E.E._y$ values for the interval and continuous datasets were significantly different after these analyses. These data are represented in Figure 3.3A and B by the bars on the left of each study. Overall, these data indicate that $T_{skin\text{-}insul}$ alone can account for a

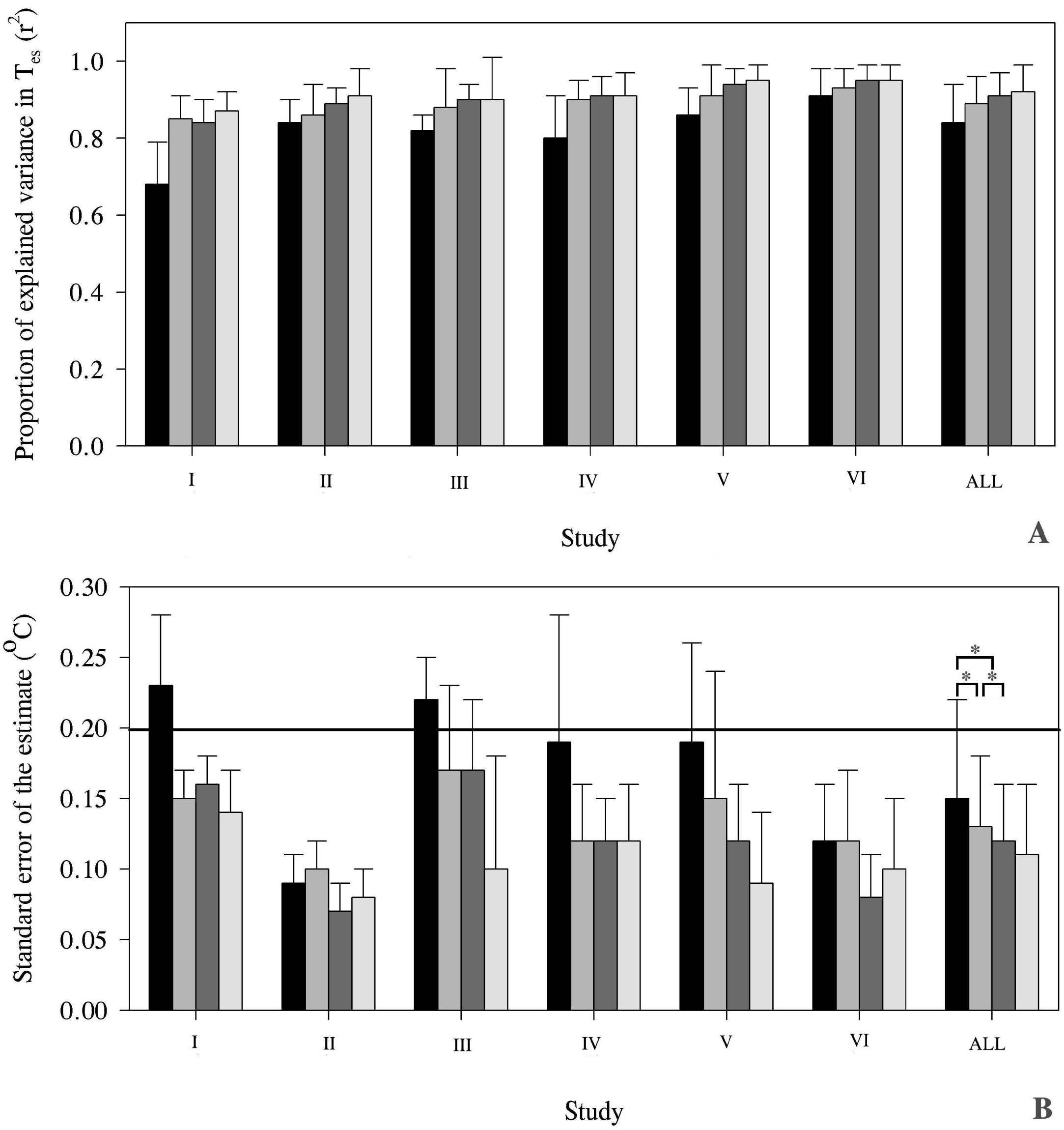


**Figure 3.3:** Prediction of oesophageal temperature ($T_{es}$): individual analysis. A-Pearson correlation coefficient squared values. B- Standard error of the estimate values. Data are for individual trials, grouped by study and are the result of regression analysis. Data are means for each study, with standard deviations. Study Legend: I = Taylor *et al*. (1998): $T_a$=25°C; II = Wilsmore (1997):$T_a$= 27°C; III = Taylor *et al*. (1998): $T_a$=33°C; IV = Armstrong and Fogarty (1999): $T_a$=33°C; V = Taylor *et al*. (1998): $T_a$=40°C; VI = Wilsmore (1997): $T_a$=40°C; All = All data combined. Legend: ■ Use of insulated skin temperature only: continuous data; □ Use of insulated skin temperature only: interval data; ■ Use of multiple predictor variables: continuous data; □ Use of multiple predictor variables: interval data. Asterisks indicate sources of significant difference- $p<0.05$. The dark line at 0.20°C indicates the desired target $S.E.E._{y.}$ Abbreviations: $T_{es}$=Oesophageal temperature; $T_a$= Air Temperature at which the data were collected.

sufficient level of variance in $T_{es}$, with the additional predictor levels adding small (though statistically significant) improvements.

3. A comparison across studies revealed the interval data set was more accurate and overall considered superior to the continuous data set with the exception of studies II and VI. In these two studies, the average $S.E.E._y$ of the individual trials in the continuous dataset was lower than the interval dataset, indicating a higher level of accuracy in the continuous analyses (Figure 3.3B). This difference was most apparent in the simple linear regression analyses of both continuous and interval data. The difference between the interval and continuous data sets may be explained by:
   - The frequency at which the data were sampled varied between the studies, and therefore the number of data points within each trial varied widely. It may be considered that using data collected every 5-15 sec may be inappropriate to detect changes in $T_{es}$. Such variations may be due to factors other than a change in $T_{es}$, for example the effect of swallowing which lowers the measured $T_{es}$. To reduce the affect of this artefact, a one-minute rolling average of $T_{es}$ was used for subsequent analyses.
   - The use of perceived exertion, a measurement only recorded during exercise, meant that the interval data set only contained data collected during exercise. It may be considered that the use of exercise only data in the interval analysis, rather than a combination of exercise and rest, may have impacted on the accuracy of the prediction equations. The inclusion of resting data in the analyses was justified by the findings of Taylor *et al.* (1998) who identified that the inclusion of non-exercising data did not alter the relationship between $T_{es}$ and $T_{skin\text{-}insul}$, though the final prediction equations developed in that research were derived from exercise-only data.

To support the suggestion that resting data may impact on the prediction of $T_{es}$, it may be noted that in the data collected from studies II and VI (the same research protocol that did not include rest periods), that the $S.E.E._y$ values were typically lower than the other studies, and that smaller differences existed between interval and continuous data sets. The lack of difference between the interval and continuous data sets in these studies indicated that the number of data points / frequency of data collection had little bearing on the accuracy of the equations, and that the key difference may be due to the inclusion of resting data in the analyses. This presumption was tested in the following analyses.

**3.2.1.3 Effect of resting data on the prediction of oesophageal temperature**

In the initial simple linear regression analyses, it was ascertained that more of the variance in $T_{es}$ could be explained in the interval data set than the continuous data set, and that the $S.E.E._y$ values were markedly lower in studies that did not include resting data (Studies II and VI: Wilsmore, 1997). It may be considered that the significant differences (between continuous and interval data sets) observed in the analysis of $T_{skin\text{-}insul}$ were likely to be due to the inclusion of resting data, and to a lesser extent, related to the number of data points analysed.

*3.2.1.3.1 Methods*

The continuous data set from Section 3.2.1.1 was separated into data collected only during exercise and data collected only during rest. Simple linear regression (Equation 3.4) was then performed on each trial, using $T_{skin\text{-}insul}$ to predict $T_{es}$ and assess the role of rest on the prediction of $T_{es}$ using $T_{skin\text{-}insul}$ only. A paired t-test was used to compare the correlation squared and $S.E.E._y$ values obtained from the simple linear regression analyses for rest and exercise, and was compare to the continuous data[4].

*3.2.1.3.2 Results and discussion*

The prediction equations for individual trials are contained in Appendix A. Figures 3.4A and B revealed that differences existed in the ability to predict $T_{es}$, between the

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The continuous data from all combined in Section 3.2.1, was modified to only use data from Studies I, III, IV and V to ensure a true comparison rest only and exercise only data, and that these analyses also differed when compared with the initial continuous analysis. The major finding was that by separating the rest and exercise data, a significantly more accurate prediction model was able to be created ($P < 0.05$). The average $S.E.E._y$ value and the standard deviations of all data were 0.2°C or lower, indicating that the desired level could be attained if exercise data was considered in a separate analysis. Most analyses continued to demonstrate a high $r^2$ value, with the mean value being approximately 0.8 (excluding Study I).

On the basis of the current analyses, the inclusion of rest data reduces the accuracy of predicting $T_{es}$, and therefore the rest and exercise data will be considered as separate datasets from this point, with the focus being on predicting $T_{es}$ during exercise as this is the most crucial time for development of heat illness. It is proposed that a different relationship between $T_{skin\text{-}insul}$ and $T_{es}$ existed during rest compared to exercise, and to maintain the accuracy of predicting rising $T_{es}$, the data collected during rest were excluded from further analyses. There was insufficient rest data available to make a valid prediction of $T_{es}$ in this situation.

#### 3.2.1.4 Conclusions regarding analysis of individual experimental trials

The preceding analyses used individual trials to predict $T_{es}$ using univariate and multivariate analyses. Within any given experimental setting, the ability to predict $T_{es}$ from physiological or psychophysical measures was high, yet between-subject variations were pronounced. The accuracy was highest when exercise data only were used, and when multiple predictor variables were available for inclusion in the equation. The inclusion of additional variables reduced the $S.E.E._y$ by an average of less than 0.05°C, the lowest measurable change for $T_{es}$. Therefore, in most cases, $T_{skin\text{-}insul}$ may stand alone as a predictor of $T_{es}$ if individual analyses are made.

Several practical considerations may be raised when considering the use of individual analyses to predict $T_{es}$, that limit the use of these equations in a field environment:

1. As the prediction equations had a high level of difference in their intercept

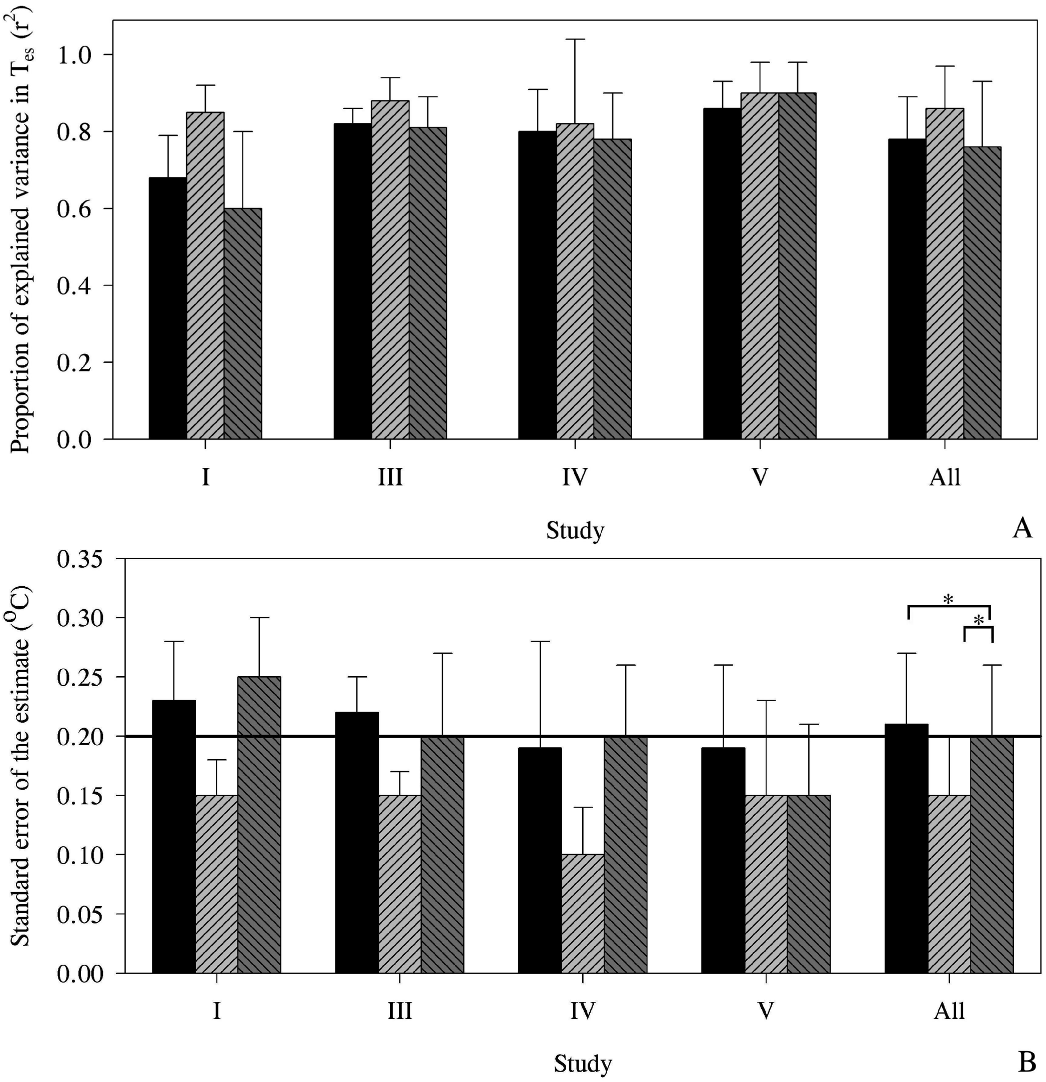


**Figure 3.4**: Prediction of oesophageal temperature using insulated skin temperature only: continuous, exercise and resting data analysis. A-Pearson correlation coefficient squared values. B- Standard error of the estimate values. Data are for individual trials, grouped by study and are the result of regression analysis. Data are means for each study, with standard deviations. Study legend: I = Taylor *et al.* (1998): $T_a$=25°C; III = Taylor *et al.* (1998): $T_a$=33°C; IV = Armstrong and Fogarty (1999): $T_a$=33°C; V = Taylor *et al.* (1998): $T_a$=40°C; Legend: Continuous data; Exercise data; Rest data; Asterisks indicate sources of significant difference- $p<0.05$.The dark line at 0.20°C indicates the desired target *S.E.E.*$_{y.}$ Abbreviations: $T_{es}$= Oesophageal temperature, $T_a$= Air temperature at which the data were collected.

and slope, a generic equation could not be developed that would suffice for all subjects based on these analyses alone. Therefore each individual would require heat stress testing prior to heat exposure to ascertain the model required for analysis.

2. The efficacy of these equations to an individual person under different environmental-exercise conditions, and different trials conducted under identical conditions is unknown.
3. Many different variables were included in each regression model and whilst some consistencies were observed, such as the dominance of $T_{skin-insul}$ as a predictor model at high $T_a$, the variety of variables required limited the practical use of individual models for each individual.

The above mentioned issues reduce the practical application of using individual regression models for the prediction of $T_{es}$, and therefore make this method less appropriate for use in a practical setting. To address theses issues, and to provide a more generalised model that may be used for a range of individuals, future analyses combined data collected within the same study.

### 3.2.2 Prediction of oesophageal temperature: within study analysis

Taylor *et al.* (1998) overcame the practical issues of using individual analysis to predict $T_{es}$, by combining the trials collected at the same $T_a$ to create one single equation that could be used to predict $T_{es}$ at a given $T_a$ and environment (*i.e.* similar clothing, and type of exercise performed). This created a model that was more suited to a practical application than the individual models described above. The premise for this technique is supported by data presented in Figure 3.5, in which the similarities in the regression lines for each individual trial (graphed by study for $T_{skin-insul}$ regressed against $T_{es}$) were observed. This indicated the potential for one regression equation to be used for each set of conditions. It may also be observed in Figure 3.5 that the regression lines become more homogenous as the $T_a$ at which the data were collected increased. Whilst using this technique decreases the accuracy of the equations, it increases the practical use for personal monitoring.

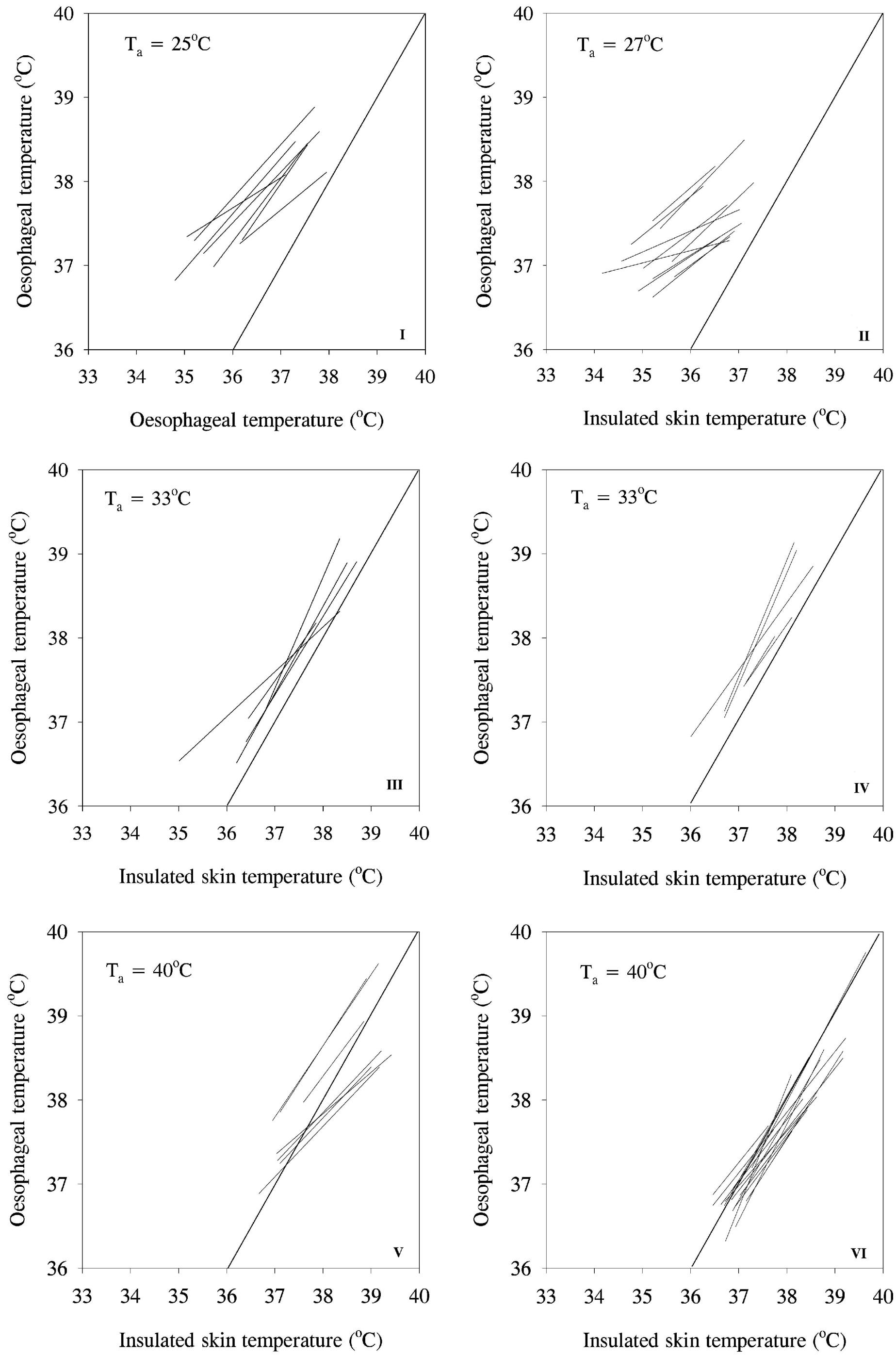


**Figure 3.5:** Relationship between insulated skin temperature and oesophageal temperature for individual trials across different studies. Study legend: I = Taylor *et al*. (1998): $T_a$=25°C; II = Wilsmore (1997):$T_a$= 27°C; III = Taylor *et al*. (1998): $T_a$=33°C; IV = Armstrong and Fogarty (1999): $T_a$=33°C; V = Taylor *et al*. (1998): $T_a$=40°C; VI = Wilsmore (1997): $T_a$=40°C. Line of identity provided in each graph. Abbreviations: $T_a$ = Air temperature at which the data were collected.

### 3.2.2.1 Methods

All the trials completed within each study, were combined into one analysis. The data used for this analysis were exercise-only, with a 1-min sampling rate, and a 3-minute rolling average. Four analyses were performed on each study to ascertain the merit of incorporating physical, psychophysical and subject characteristics into the equation (Table 3.3). With the exception of the first analysis, no variables were forced into any equation, with the variable entry being determined wholly by the *F* value as outlined in section 3.2.1.1.1.

The $S.E.E._y$ and $r^2$ values were compared across the different analyses, and across the different $T_a$. The analyses determined the effect of the inclusion of additional measurements in the regression pool on the equations, and the difference between the data collected at different $T_a$. The regression statistics were compared between the individual and combined analyses. Descriptive statistics were used for these comparisons.

### 3.2.2.2 Results and discussion

Combining data collected during the same study at the same $T_a$ resulted overall in equations that lacked the accuracy of the individual models. The summary of findings is indicated below:

1. Using $T_{skin\text{-}insul}$ to predict $T_{es}$ across an entire study (Analysis One) resulted in lower correlation squared values ($r^2 = 0.16\text{-}0.87$) than the average of the individual trials ($r^2 = 0.68\text{-}0.91$) for the corresponding studies, and are at a level to be considered to be unsatisfactory in Studies I, II, IV and V (solid black bars in Figure 3.6A). The mean values for all trials combined was 0.29 lower than the average of the same individual trials. The $S.E.E._y$, illustrated for each study in Figure 3.6B, averaged 0.2°C higher in the grouped data than for the average obtained for each individual trial (when averaged by database), and was 0.05-0.15°C greater than the maximum $S.E.E._y$ value indicating the greater error in the prediction model by combining the data.

**Table 3.3:** Measurements available for inclusion in the four stages of regression modelling

| | **Measurements available for inclusion in regression model** | | | |
|---|---|---|---|---|
| **Analysis** | Insulated skin temperature | Heart rate, mean skin temperature, work rate | Thermal sensation, thermal Discomfort, Rating of perceived exertion (whole body) | Height, mass, BMI, Sum of six skinfolds, mass normalised for height, surface area, surface area:mass, age and sweat loss, relative adiposity |
| Analysis One | ✓ | | | |
| Analysis Two (Physiological) | ✓ | ✓ | | |
| Analysis Three (Psycholphysical) | ✓ | ✓ | ✓ | |
| Analysis Four (Physical) | ✓ | ✓ | ✓ | ✓ |

Note: Calculations for physical measurements: Sum of six skinfolds = triceps + subscapular+ supraspinale + abdominale+ front thigh + medial calf; Body Mass Index (BMI: Ross and Ward, 1984) = Weight (kg)/ height ($m^2$); Mass Normalised for height= Mass(kg) *1(170.18/height (cms))$^3$ (Ross and Ward 1984), Surface Area ($m^2$: Dubois and Dubois, 1916(DuBois and DuBois 1916))= 0.202 x mass$^{0.425}$ * height * $^{0.725}$; Surface area: Mass ratio = Surface area ($m^2$)/ mass (kg); Relative adipostity (Ross and Ward 1984)= sum of six skinfolds *170.18/height (cms)

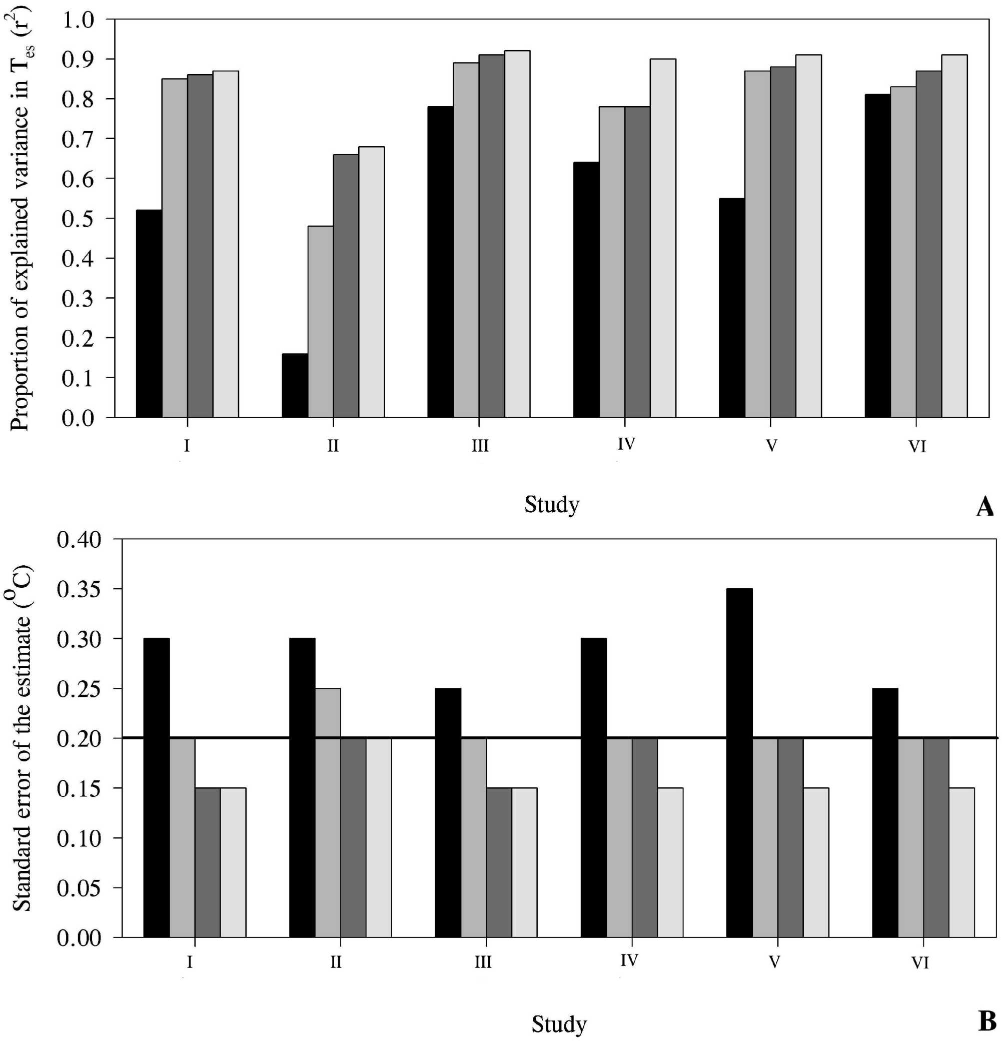


**Figure 3.6:** Prediction of oesophageal temperature: Study Analysis.A: -Pearson correlation coefficient squared values. B- Standard error of the estimate values. Data are for trials grouped by study and are the result of regression analysis. Study legend: I = Taylor *et al.* (1998): 25°C; II = Wilsmore (1997):27°C; III = Taylor *et al.*(1998):33°C; IV = Armstrong and Fogarty (1999):33°C; V=Taylor *et al.* (1998): 40°C; VI=Wilsmore (1997): 40°C. Legend: Use of insulated skin temperature as predictor variable (Analysis One); Use of multiple physiological measurements and insulated skin temperature as predictor variables (Analysis Two); Use of multiple physiological, psychophysical measurements and insulated skin temperature as predictor variables Multiple linear regression with physiological and psychophysical variables available for inclusion (Analysis Three); Use of multiple physiological, psychophysical, physical measurements and insulated skin temperature as predictor variables (Analysis Four).The dark line at 0.20°C indicates the desired target *S.E.E.*$_{y.}$ Abbreviations: $T_{es}$= Oesophageal temperature.

2. Increasing the number of measurements available for inclusion was able to increase the ability of the prediction models (second box from left: Figures 3.6A and B) from using $T_{skin\text{-}insul}$ alone to predict $T_{es}$. The correlation squared value for each study increased by an average of 0.21 (range 0.02-0.33), whilst an average decrease of 0.09°C (range 0.05-0.15°C) was observed in the $S.E.E._y$ for the addition of physiological measurements, and these were the most influential predictor variables after $T_{skin\text{-}insul}$. The decrease observed in the $S.E.E._y$ lowered it to a level deemed appropriate for a personal heat strain monitor (≤0.2°C) in all studies, with the exception of Study II. The inclusion of psychophysical measures as predictor variables made only small improvements to the prediction models (with the exception of Study II which was still lower than the other studies, but attained the target level of $S.E.E._y$). Similar small, but not meaningful, improvements were observed with the introduction of physical characteristics. This suggests that the addition of only physiological measurements may be all that is required to develop an appropriate model at higher $T_a$.
3. Comparison of the final regression statistics obtained for each study, following completion of all above analyses, indicated the mean values were very similar to those obtained using grouped data (comparison of Figures 3.3 and 3.6). The differences observed were considered insignificant with the exception of Study II. Whilst Study II obtained excellent accuracy in the individual trials, the act of combining the data resulted in $T_{skin\text{-}insul}$ alone being a poor predictor of $T_{es}$. This was expected given the wide variation in slope and intercepts for individual trials as observed in Figure 3.5B.
4. The role of psychophysical measurements in a personal heat strain monitor to assist in predicting $T_{es}$ is questionable. This may relate to differences in individual perception of perceived exertion, thermal sensation and discomfort, and experience in utilising these scales appropriately.
5. It was observed that at higher $T_a$ the inclusion of physical characteristics (as per analysis four) added little to improving the accuracy of the regression models, compared to improved accuracy at mild-moderate $T_a$. This result

indicated that physical characteristics may have a greater role in predicting $T_{es}$ at lower $T_a$. This relationship currently remains inexplicable, as the equations indicate no clear trends in the physical characteristics used, with differing regression coefficients (the same variable being negative and positive within different studies).

6. The poor results obtained by combining trials in Study II suggested that $T_{skin-insul}$ was a very poor predictor of $T_{es}$ under these experimental conditions. The major differences between the data of Studies I, III and V and between Studies II and VI were the type of clothing worn and the mode of exercise (Table 3.1). These factors are the potential reason for the poor relationship observed between $T_{skin-insul}$ and $T_{es}$ in Study II compared to Study I. The relevance of Study II to the application for which the heat strain monitor is designed is questionable as subjects were in a 27°C environment, wearing only shorts. This is a scenario that would be unlikely to be encountered in the Defence Force or Industry where the heat strain monitor may be used. To elaborate on the potential effects of the differences in the studies, the clothing worn in Study I may have provided additional insulation from the environmental conditions (in addition to that provided by the insulation over the $T_{skin-insul}$ thermistor), reducing any effect of $T_a$ that may have resulted in a cooling effect on the skin, and subsequently $T_{skin-insul}$. Recumbent cycling, as used in Study II and VI, may have partly dislodged the insulation on the back of the subjects, thereby increasing the influence of $T_a$, which was considerably lower than that of $T_{es}$. The effect of this would be less noticeable in an $T_a$ of 40°C where the skin-air temperature gradient was reduced. This theory is partially supported by Figure 3.5 in which $T_{skin-insul}$ exceeded $T_{es}$ on a regular basis at a $T_a$ of 40°C. Due to the variation in the experimental methods in three different studies there was no way to assess the potential reasons for these differences, and therefore the differences between the data must be anticipated in data collected under these environmental and clothing conditions.

### 3.2.3 Prediction of oesophageal temperature: database analysis

Four primary areas were identified in which the research studies differed: clothing, exercise mode, work rate and $T_a$ (Table 3.1). The equations developed in the previous analyses were only valid if used under the specific conditions investigated within each study as the effect of each of these factors on the relationship between $T_{es}$ and $T_{skin\text{-}insul}$ could not be isolated without further studies, and the practicality of using these equations for personal heat strain monitoring is reduced.

It had been established that $T_a$ has an effect on the relationship between $T_{skin\text{-}insul}$ and $T_{es}$ (Taylor *et al.*, 1998). This may also be observed in Figure 3.7, where trials within the same research study were combined, and line of least squares best fit was drawn, making it possible to compare data across all research studies. There were many similarities in the slopes and intercepts of data collected at the same $T_a$, predominantly at an $T_a$ of 33°C and higher. As a result of these similarities, and to increase the practical use of the equations, the data in the next analyses were combined, so that all data collected at the same $T_a$ were analysed together in an attempt to develop a more practical model.

Furthermore, although the aim of this project was to develop a model that may be used under most conditions where heat stress and heat illness may be an issue, it is considered that at the lower range of $T_a$ analysed, the risk of developing potentially fatal heat stroke is low (Wyndham, 1974). Thus, a greater degree of error in the equations developed at this temperature may be allowable as the risk of fatality is significantly lower.

#### 3.2.3.1 Methods

The same methods of analysis were performed as for Section 3.2.2. These analyses differed in that the data were grouped by the $T_a$ at which the data were collected. Air temperature was added as a predictor variable in the combined data collected at a $T_a$ of 25°C and 27°C, and clothing insulation was added as a predictor variable for all databases, with the minimal clothing being assigned an insulation value of 0.12 clo

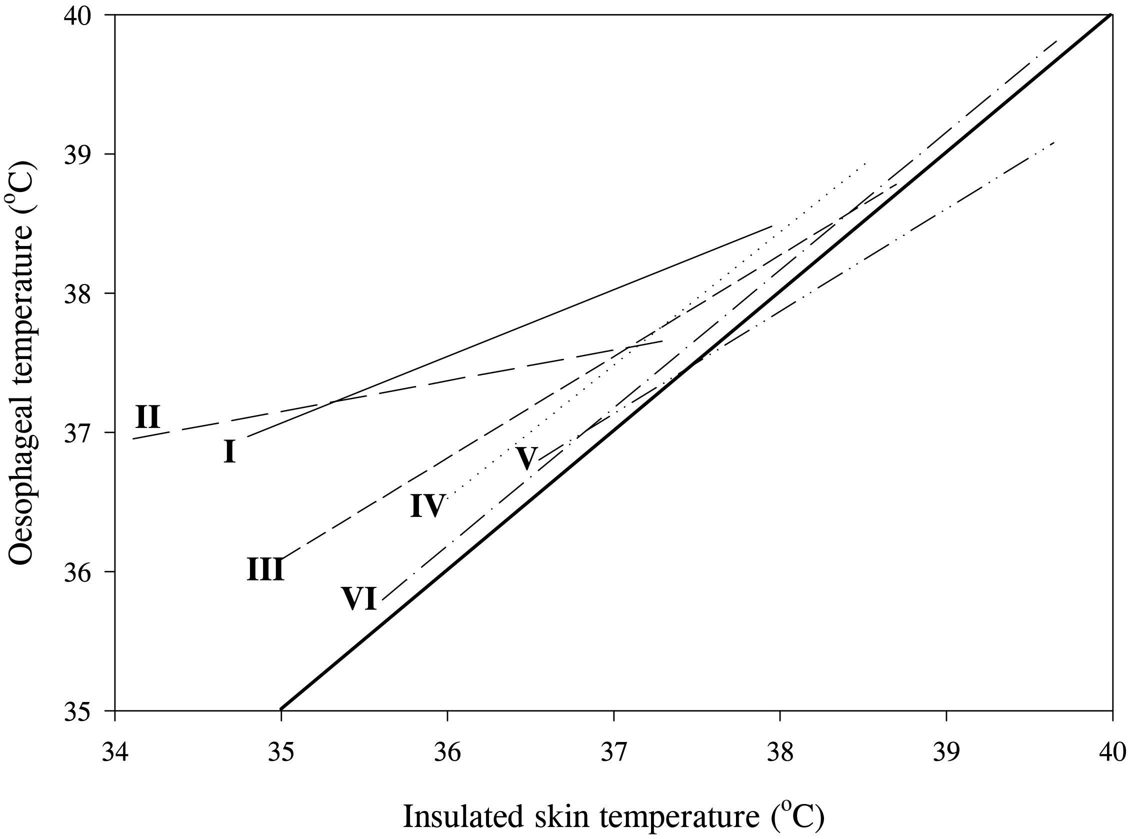


**Figure 3.7:** Relationship between insulated skin and oesophageal temperatures across all studies. Line of least squares best fit for each study. Study legend: I = Taylor *et al*. (1998): 25°C; II = Wilsmore (1997):27°C; III = Taylor *et al.* (1998): 33°C; IV = Armstrong and Fogarty (1999); V = Taylor *et al.* (1998): 40°C; VI = Wilsmore (1997):40°C.

and the army combat uniform being assigned an insulation value of 0.9 clo. Refer to Table 3.3 for the measurements available for inclusion in each of the four analyses.

#### 3.2.3.2 Results and discussion

The regression equations for each analysis may be found in Appendix A. A summary of the regression statistics is found in Figures 3.8A and B, and these were examined in two ways: the effects of each type of analysis on the prediction of $T_{es}$; and the difference between the analysis types at each $T_a$. The comparison of the results obtained across the databases may be summarised by three main points:

1. The most obvious difference in the analyses was that the level of accuracy of the prediction equations varied according to the database. Database One was markedly poorer at explaining the variance in $T_{es}$, and the *S.E.E* $_y$ values were higher than those at higher $T_a$ (refer to light grey box on the far left of each database). This indicated that the ability of $T_{skin\text{-}insul}$ to predict $T_{es}$ varied depending upon the $T_a$, and that higher $T_a$ are associated with improved ability of $T_{skin\text{-}insul}$ to predict $T_{es}$.
2. With the addition of multiple predictor variables (Analyses Two to Four) the accuracy of the databases became similar, and between Analysis Two and Four, the changes in the regression statistics were minimal or showed no change. Any changes observed were predominantly due to the introduction of physiological measures which appeared to reduce any effects of $T_{skin\text{-}insul}$ being a poor predictor of $T_{es}$ at lower $T_a$. This is also suggestive that the addition of physiological variables makes a major contribution to improving the ability to predict $T_{es}$, and highlights that when $T_{skin\text{-}insul}$ is combined with other variables that the ability to predict $T_{es}$ is enhanced significantly. In Databases Two and Three, the target *S.E.E.* $_y$ of 0.2°C was attained after inclusion of the physiological variables (Analysis Two), and was the result of a 0.05 and 0.10°C respective reduction in the *S.E.E.* $_y$ from Analysis One. The addition of physical characteristics as predictor variables did not lower the *S.E.E.* $_y$ in any database.

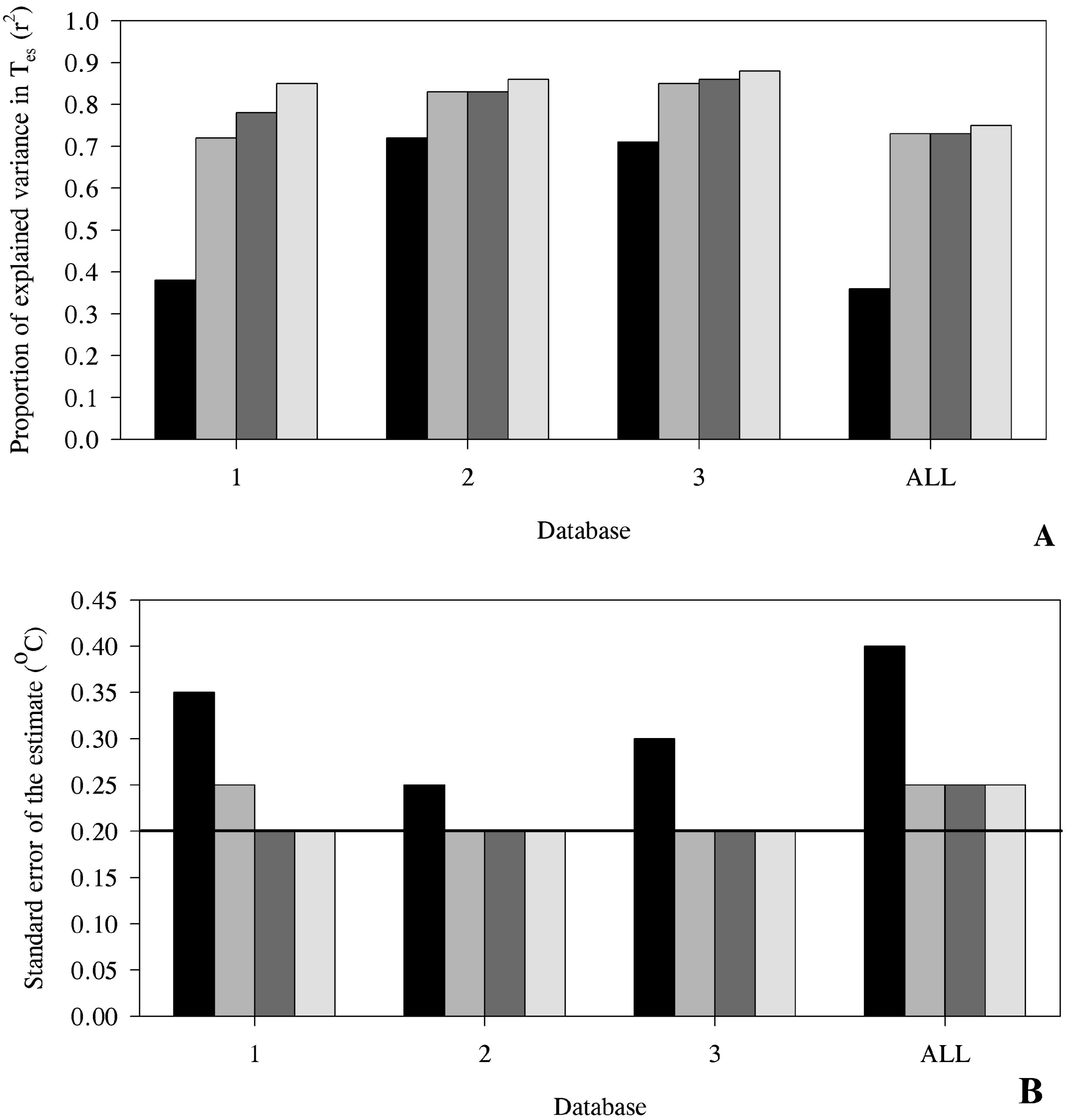


**Figure 3.8**: Prediction of oesophageal temperature: Database Analysis. A-Pearson correlation coefficient squared values. B- Standard error of the estimate values. Data are combined for studies collected at the same air temperature and are the result of regression analysis. Database 1 = data collected at 25 and 27°C; Database 2 = data collected at an air temperature of 33°C; Database 3= data collected at an air temperature of 40°C. Legend: Simple linear regression of insulated skin temperature only (Analysis One); Multiple linear regression with other physiological measurements included (Analysis Two); Multiple linear regression with physiological and psychophysical variables available for inclusion (Analysis Three); Multiple linear regression with physiological, psychophysical and subject characteristics available for inclusion (Analysis Four).The dark line at 0.20°C indicates the desired target $S.E.E._{y.}$

3. When all data were combined, the $S.E.E._y$ was 0.25°C. This was 0.05°C higher than the acceptable threshold of 0.2 °C, and 0.05°C higher than the results of Analysis Four at each $T_a$. Combining data was least effective when only $T_{skin\text{-}insul}$ was used to predict $T_{es}$. Grouping all data collected did not produce an equation that would be deemed accurate enough for use in a commercial environment, and therefore data should remain segregated by the $T_a$ at which it was collected for use in a heat strain monitor

Based on the above findings, the implications for a heat strain monitor are that whilst the prediction models developed utilising data grouped by $T_a$, were less accurate than when the data were grouped only by the study in which it was collected, the models developed in these analyses demonstrated greater practical significance since they attained the appropriate degree of accuracy after inclusion of multiple variables. In regards to the measures required to attain an appropriate level of accuracy at an $T_a$ of 33°C or above, the only variables required to predict $T_{es}$ to an acceptable level of accuracy were $T_{skin\text{-}insul}$ and the measures of $f_c$, mean skin temperature, workload and / or clothing (refer to Appendix A). This finding potentially negates the need to collect the physical characteristics of each user, and the intermittent collection of psychophysical data. Prior to eliminating these or other variables, the models would need to be tested on independent data. At an $T_a$ of 25-27°C, the inclusion of psychophysical measurements was required to attain an equation that was considered accurate enough for a personal monitoring system.

### 3.3 PREDICTION OF CHANGES IN OESOPHAGEAL TEMPERATURE USING INSULATED SKIN TEMPERATURE

Occupational standards for physiological monitoring recommend work termination when threshold limits for $T_c$ have been attained, and are outlined in Section 2.5. These standards are based on measured $T_c$, or the change in $T_c$ (National Institute of Occupational Safety and Health, 1986). Until the present analyses, investigations focussed on predicting the measured $T_{es}$. It is anticipated that by predicting the change in $T_{es}$ the effect of individual differences in the offset of the $T_{skin\text{-}insul}$ from the $T_{es}$

measurement would be eliminated. This is based on two observations:

1. The similarities in slopes observed in the regression lines and their relationship to the line of identity (Figure 3.5).
2. The differences in the intercepts add to the error in the prediction of $T_{es}$.

This would allow the developed index to be used in conjunction with recommended guidelines for exposure (*e.g.* 0.8°C change=warning, and 1.0°C change=danger; International Standards Organisation, 1982; Cited in National Institute of Occupational Safety and Health, 1986). It is also proposed that a high level of accuracy could be achieved by using $T_{skin\text{-}insul}$ change data in conjunction with the measured $T_{es}$ (or similar measure of $T_c$) to develop a calibrated measure of $T_{skin\text{-}insul}$.

The practical considerations in using a calibrated measure of $T_{skin\text{-}insul}$ in a commercial monitor may outweigh the advantages, as it requires an accurate assessment of $T_c$ during the initial stages of the heat stress. However, to develop an understanding of the best means possible to predict $T_{es}$, it was necessary to undertake a preliminary investigation into the accuracy of this technique.

### **3.3.1 Methods**

All data collected at the same $T_a$ were combined as a single database, as in Section 3.2.3. Two methods of analysing the data were used for comparison with the analyses previously completed (referred to as unadjusted data):

1. Prediction of the change in $T_{es}$ from the change in $T_{skin\text{-}insul}$, from 10 min after the start of exercise (referred to as change data).
2. Prediction of the measured $T_{es}$ from the $T_{skin\text{-}insul}$ calibrated to $T_{es}$ at 10 min (referred to as calibrated data).

Both analyses removed the effect of the initial offset between $T_{es}$ and $T_{skin\text{-}insul}$, but would start at either a consistent baseline (zero for the change calculations), or a baseline calibrated to the $T_{es}$ at 10 min into the exercise protocol (calibration). For both of these methods to be accurate and reliable, they assume that $T_{skin\text{-}insul}$ had a 1:1 relationship with $T_{es}$. The change in $T_{es}$ and $T_{skin\text{-}insul}$ was calculated for all trials 10 min from commencement of the trial ($T_{es10}$) to remove the effect of the differences in the offset between $T_{es}$ and $T_{skin\text{-}insul}$ in the initial stages[5]. The procedure for calibrating $T_{skin\text{-}insul}$ is demonstrated in Equation 3.8.

$$T_{es(p)} = (T_{es10} - T_{skin\text{-}insul10}) + T_{skin\text{-}insul(x)} \qquad \textbf{Equation 3.8}$$

*Where:*

$T_{es(p)}$ = predicted oesophageal temperature
$T_{es10}$ = measured oesophageal temperature at 10 min
$T_{skin\text{-}insul10}$ = insulated skin temperature at 10 min
$T_{skin\text{-}insulx}$ = insulated skin temperature at current time point

To assess the predictive ability of each of the new measurements, simple linear regression was used to predict $T_{es}$, or the change in $T_{es}$ from both the unadjusted, and adjusted (calibrated and change) data. The unadjusted analyses were recalculated to exclude the first 10 min of data to allow a direct comparison between analysis types. The precision of each method of analysis was assessed by comparing the correlation squared and $S.E.E._y$ values.

### 3.3.2 Results and discussion

The regression equations from the simple linear regression analyses are included in Appendix A, and the regression statistics are summarised in Figure 3.9A and B. The key findings of these analyses are identified below:

1. There were few differences evident between the proportion of explained variance in $T_{es}$ of the calibrated and change models across each $T_a$, with the exception of Database Two. It was evident in Database Two that the 'unadjusted' analysis (light grey bars on Figure 3.9A) was superior.
2. The accuracy of predicting $T_{es}$ at lower $T_a$ (Database One) was decreased compared to at an $T_a$ of 33°C and above and confirms $T_{skin\text{-}insul}$ is least effective as a predictor variable for $T_{es}$ at lower $T_a$.

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5

A trend was evident for $T_{skin\text{-}insul}$ to show a large increase at the start of every trial which is associated with the change from a cool-warm environment, and an increase in skin temperature. As this change would have a significant effect on calculating the change in predicted $T_{es}$, the initial 10 min of data was removed.

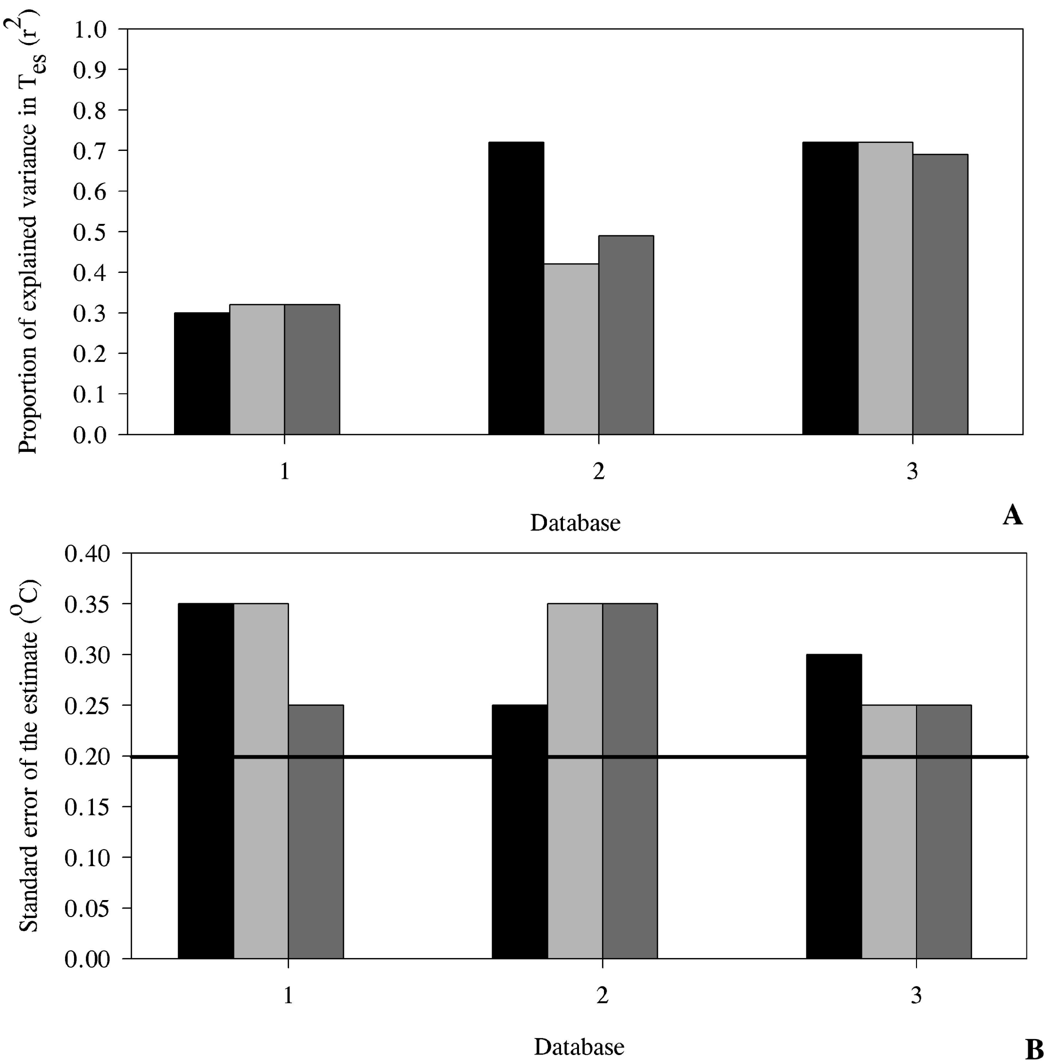


**Figure 3.9:** Prediction of oesophageal temperatures using three methods. A- Pearson correlation squared values; B- Standard error of the estimate values. Database 1 = Data collected at an air temperature of 25 and 27°C; Database 2 = data collected at an air temperature of 33°C; Database 3 = data collected at an air temperature of 40°C. Legend: Unadjusted analysis: no adjustments were made; Calibrated analysis: insulated skin temperature was calibrated to oesophageal temperature at 10-min; Change analysis: the change value from time 10-min was used for oesophageal and insulated skin temperature. The dark line at 0.20°C indicates the desired target *S.E.E.*$_{y.}$ Abbreviations: $T_{es}$ = Oesophageal temperature.

3. There were no trends in the *S.E.E.*$_y$ values across all $T_a$ that indicated a superior technique. In Database One, predicting the change in $T_{es}$ was a more accurate technique than calibrating the $T_{skin\text{-}insul}$ or predicting the actual $T_{es}$. In Database Two, predicting the change in $T_{es}$ or using a calibrated $T_{skin\text{-}insul}$ to predict $T_{es}$ reduced the accuracy of the prediction models. A 0.05°C difference in the *S.E.E.*$_y$ values in Database Three was observed between the methods (Figure 3.9). No analysis attained the target *S.E.E.*$_y$ or lower (0.20°C).
4. Based on the combined regression statistics, the unadjusted analysis was considered the most consistently accurate analysis across all temperature ranges. This was most notable in Database Two, where the correlation squared value was up to 30% higher in the unadjusted analysis than the calibrated analysis, with the *S.E.E.*$_y$ value being 0.10°C lower. In Database Three, there were few differences between the types of analyses, with less than 0.02°C difference in the *S.E.E.*$_y$ values, and 7% difference in the correlation squared values.

To summarise, the most suitable technique for the prediction of $T_{es}$ was dependant upon the $T_a$ at which the data was collected. As no model was clearly superior across all $T_a$, consideration for the best technique was given to three points:

1. The conditions under which heat illness was most likely to be an issue;
2. The practical application of the analysis; and
3. The ability to use the measurement in the majority of heat stress indices.

Based on these criteria, the method of choice for further analyses is the prediction of $T_{es}$ based on the unadjusted $T_{skin\text{-}insul}$ measurement. The following points describe how this conclusion was reached:

1. Only a small difference in the regression statistics was observed between all techniques at an $T_a$ of 40°C. This indicated that at a high $T_a$, the technique used had minimal impact on the accuracy of the prediction.
2. In Database Two (33°C), the unadjusted analysis was clearly superior, and there was a large difference between the explained variance values across the

analyses.

3. The ability to accurately gain a precise $T_{es}$ measurement for calibration after the start of exercise or work was considered impractical and increased the risk of error.

## 3.4 DEVELOPMENT OF THE FINAL PREDICTION EQUATIONS

To predict a valid and reliable surrogate of $T_{es}$ across a range of environmental conditions, a prediction model that was appropriately responsive to $T_{es}$ was required. Based on the above observations and equations outlined in Appendix A, several factors were instrumental to the development of these equations:

1. Insulated skin temperature, $f_c$ and mean skin temperature ($\overline{T}_{sk}$) were the most powerful predictive information across the range of $T_a$ studied. The most powerful predictor variable was dependant upon the $T_a$ at which the data were collected and was $f_c$ at 25-27°C, and $T_{skin\text{-}insul}$ above this $T_a$.
2. Estimation of work rate did not contribute markedly to the prediction of $T_{es}$.
3. Across all databases, it was more accurate to predict the actual $T_{es}$ rather than the change in $T_{es}$.
4. Data from the same $T_a$ incorporated together created models that were less accurate than individual analyses, but were more practical for use in a commercial monitor.
5. Exercise and rest phases were considered separately in the analyses to allow for greater accuracy during exercise, which is the most critical period of $T_{es}$ change. Minimal rest data did not allow development of separate equations.

In addition, it was considered important to find a common set of predictor variables that could be used across all conditions. Therefore the following factors were considered in determining the predictor variables that were to be used in a standard equation:

1. The contribution of $\overline{T}_{sk}$ was observed to be suitable as a predictor of $T_{es}$ in the analyses completed thus far. However $\overline{T}_{sk}$ suitability under other conditions was unknown. In addition, there are known situations where $\overline{T}_{sk}$ changed in the

opposite direction to that of $T_c$. Torii *et al.* (1992) reported a decrease in $\bar{T}_{sk}$ of up to 1.0°C during exercise in minimal clothing in 30°C and 40°C. The effect of this reduction in $\bar{T}_{sk}$ on the prediction equation would create dramatic errors in the prediction of $T_{es}$, making the prediction model unreliable in these situations, and therefore $\bar{T}_{sk}$ was discarded from further analyses.

2. Whilst the contribution of each of the subject's physical characteristics was small, these data added substantially to the explained variance in $T_{es}$ across all analyses. Therefore, these variables may be significant predictors across independent databases and should not be excluded from these analyses until further examination. Furthermore, it was critical that variables that co-varied (*e.g.* sum of six skinfolds and relative adiposity) were not used together within a prediction equation, as this compromised the integrity of the equation, without adding new information. It was considered that mass and sum of six skinfolds were the most appropriate variables to include as they have a close link with, and impact on, $T_c$.

### 3.4.1 Methods

In attempting to arrive at the most effective and functional prediction model, four groups of prediction equations were developed for each $T_a$ (25-27°C; 33°C; and 40°C) as outlined in Table 3.4. Each equation used regression modelling to derive the prediction equation. In Group A equations, simple linear regression modelling was used (Equation 3.4), with multiple linear regression modelling used to predict $T_{es}$ in equations grouped B-D (Equation 3.5). Three prediction equations were developed within each grouping, corresponding to data collected at each $T_a$. Each equation group was designed for a specific function, and a comparison of the equations was made with consideration given to the complexity of the model and variables required in the measurement to examine and compare the effectiveness of the predictor variables. The degree of complexity increased in each equation grouping from A-D (Table 3.4).

**Table 3.4:** Descriptive information for the final regression equations for the prediction of oesophageal temperature

| **Equation Grouping** | **Predictor Variables** | **Comments** |
|---|---|---|
| **Group A** | $T_{skin-insul}$ | Baseline equation; May be used in heat strain indices |
| **Group B** | $T_{skin-insul}$, and $f_c$. | Two most powerful predictor variables across all air temperatures |
| **Group C** | $T_{skin-insul}$, $f_c$, mass and sum of six skinfolds | Comparison with Group B equations to assess the role of physical characteristics that impact on thermoregulation in prediction of $T_{es}$. |
| **Group D** | $T_{skin-insul}$, RPE, mass and sum of six skinfolds | Comparison with Group C equations, and use of RPE, as the psychophysical analogue to $f_c$, to allow equation to be used in heat stress indices |

Abbreviations: $T_{skin-insul}$ = insulated skin temperature; $f_c$ = cardiac frequency; RPE = Rating of Perceived Exertion.

### 3.4.2 Results and discussion

The four regression equations for each $T_a$ are contained in Table 3.5, with the relevant regression statistics ($r^2$ and $S.E.E._y$) illustrated in Figures 3.10A and B respectively. The results may be summarised by comparing the equation groups, with a comparison of each equation across each $T_a$:

1. Equations in Group A were the least accurate prediction equations across all $T_a$. Group A equations are illustrated in Figure 3.10 as the black bars on the left side of each grouping, and at no point did these equations attain a $S.E.E._y$ equal to or below the target of 0.2°C (range 0.25-0.35°C). These equations explained the least variance in $T_{es}$, notably in the equation developed for use at an $T_a$ of 25-27°C where the correlation squared value equalled 0.39. It was expected that these would be the least accurate model as other equations were able to utilise additional predictor variables. There was a tendency for the models to become more accurate at a higher $T_a$ across the Group A prediction models indicating the effect of $T_a$ on $T_{skin\text{-}insul}$.
2. Equations developed in Group B (darker grey bars second to the left on each database in Figure 3.10) were more accurate than Group A equations at each $T_a$, with a an improved $S.E.E._y$ and correlation squared values observed for the equation developed from Database One. The $S.E.E._y$ was lower in Group B equations by 0.10-0.05°C, although it was observed that only data collected at an $T_a$ of 33°C attained the target $S.E.E._y$ of 0.2°C or less (range 0.20-0.25), indicating $T_{skin\text{-}insul}$ and $f_c$ are the only required predictor variables in this $T_a$ range. Utilising $f_c$ as a predictor in this model made positive improvements to the proportion of variance explained by the model, which were all above an $r^2$ value of 0.65. This demonstrated that $f_c$ had a significant role as a predictor of $T_{es}$, and is more appropriate for use at lower $T_a$.

**Table 3.5:** Simple and multiple linear regression models to predict oesophageal temperature using a range of predictor variables

| Model Name | Prediction Equation |
|---|---|
| **A-25** | $T_{es\text{-}predicted}$ = 24.4326 *0.3626 * $T_{skin\text{-}insul}$ |
| **A-33** | $T_{es\text{-}predicted}$ = 3.5062 *0.9182 * $T_{skin\text{-}insul}$ |
| **A-40** | $T_{es\text{-}predicted}$ = 5.4784 *0.8569 * $T_{skin\text{-}insul}$ |
| **B-25** | $T_{es\text{-}predicted}$ = 36.8285 - 0.022 * $T_{skin\text{-}insul}$ +0.0127 * $f_c$ |
| **B-33** | $T_{es\text{-}predicted}$ = 14.496 -+0.5905 * $T_{skin\text{-}insul}$ +0.0088 * $f_c$ |
| **B-40** | $T_{es\text{-}predicted}$ = 15.1623 + 0.5726 * $T_{skin\text{-}insul}$ +0.0077 * $f_c$ |
| **C-25** | $T_{es\text{-}predicted}$ = 36.8305 -0.0212* $T_{skin\text{-}insul}$ +0.0128 * $f_c$ - 0.0003* $\sum 6_{skinfolds}$ - 0.0002 * Mass |
| **C-33** | $T_{es\text{-}predicted}$ = 14.262 +0.5916* $T_{skin\text{-}insul}$ +0.0087 * $f_c$ - 0.0023* $\sum 6_{skinfolds}$ + 0.000 * Mass |
| **C-40** | $T_{es\text{-}predicted}$ = 8.933 +0.7325 * $T_{skin\text{-}insul}$ +0.0069 * $f_c$ +0.0083* $\sum 6_{skinfolds}$ - 0.0029 * Mass |
| **D-25** | $T_{es\text{-}predicteds}$ = 32.6735 +0.1251 * $T_{skin\text{-}insul}$ +0.0731 * RPE-W -0.0073* $\sum 6_{skinfolds}$ + 0.0009 * Mass |
| **D-33** | $T_{es\text{-}predicted}$ = 8.2304 +0.7878 * $T_{skin\text{-}insul}$ +0.0371 * RPE-W -0.0038* $\sum 6_{skinfolds}$ - 0.0003 * Mass |
| **D-40** | $T_{es\text{-}predicted}$ =1.78118 +0.9377 * $T_{skin\text{-}insul}$ +0.0282 * RPE-W + 0.0093* $\sum 6_{skinfolds}$ - 0.0030 * Mass |

Abbreviations: $T_{es}$ = oesophageal temperature; $T_{skin\text{-}insul}$ = insulated skin temperature; $f_c$ = cardiac frequency; $\sum 6_{skinfolds}$ = sum of six skinfolds; RPE-W= Rating of Perceived Exertion (Whole Body).

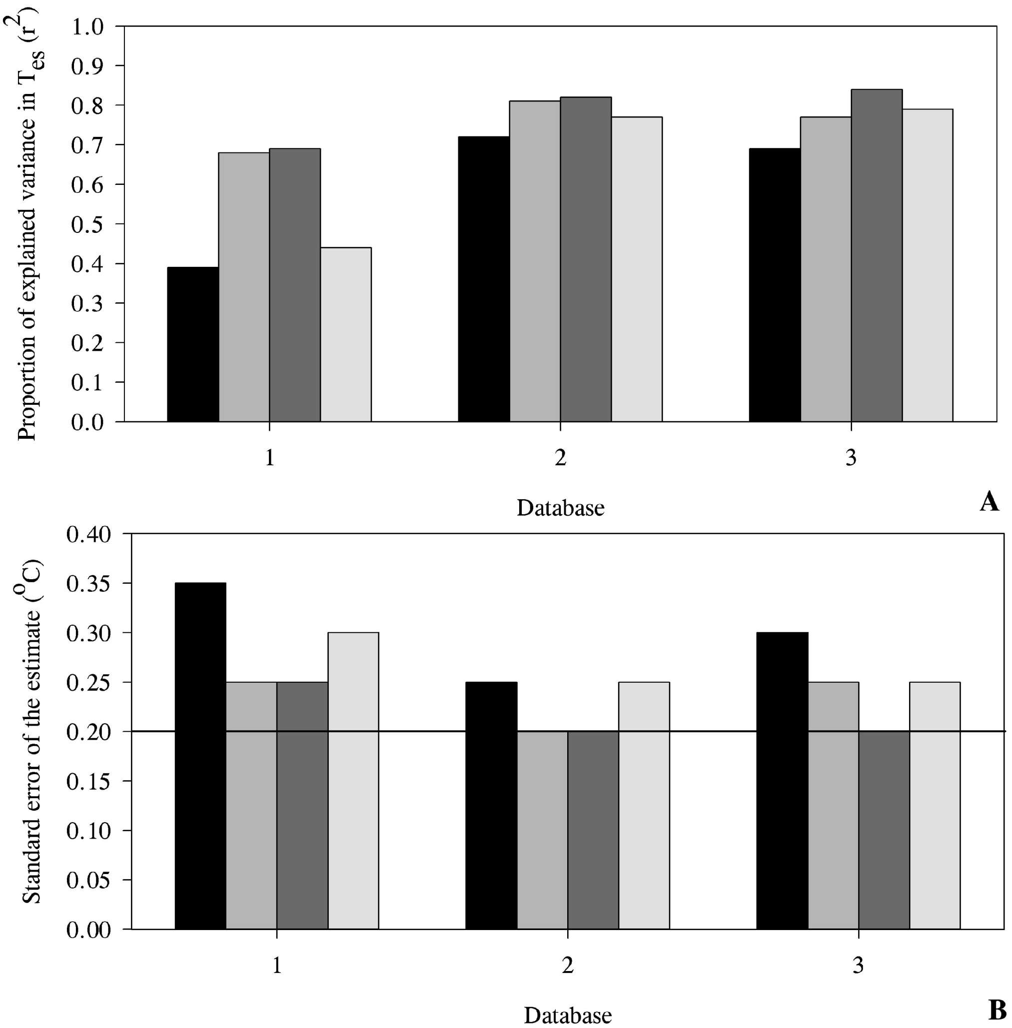


**Figure 3.10:** Prediction of oesophageal temperature: Final regression equations. A- Pearson correlation squared values; B- Standard error of the estimate values. Study Legend: Database 1 = Data collected at an air temperature of 25 and 27°C; Database 2 = data collected at an air temperature of 33°C; Database 3 = data collected at an air temperature of 40°C. Legend: Group A (Variable included in regression: insulated skin temperature only); Group B (Variables included in regression: insulated skin temperature and cardiac frequency); Group C (Variables included in regression: insulated skin temperature, cardiac frequency, sum of six skinfolds and mass); Group D (Variables included in regression: insulated skin temperature, perceived exertion, sum of six skinfolds and mass).The dark line at 0.20°C indicates the desired target $S.E.E._{y.}$ Abbreviations: $T_{es}$ = Oesophageal temperature.

The introduction of physical characteristics (Group C) as predictor variables resulted in a small increase in the accuracy of the prediction equations. It was only in equations developed at an $T_a$ of 33°C and above that the target $S.E.E._y$ of 0.2°C was attained. Similarly, an $T_a$ of 40°C was required before the individual characteristics became significant contributors to the prediction models, suggestin that it is only at higher $T_a$ that they have some role in the prediction of $T_{es}$.

3. Group D equations provided a more accurate prediction than equations in Group A, however, they were poorer than, or equivalent to, equations in Group B when compared across both regression statistics, indicating the RPE was not an effective substitute for $f_c$. This may be explained by the frequency of collection and experience in the use of the RPE scale. It may also be observed that in the light grey bars on the right side of each database in Figure 3.10, that the $S.E.E._y$ values for Group D equations were always above the target value of 0.2°C at each $T_a$, (range 0.25-0.30). The proportion of explained variance was similar to equations in Group B in Databases Two and Three, though approximately 0.25 lower in Database One (range 0.44-0.79).
4. Comparison of the prediction models suggests that if a universal prediction model is used, then the equations in Group C were most suitable for use in this model. Group C equations were the only equations to attain a $S.E.E._y$ of 0.2°C across all $T_a$. Should a monitor only be required for use in more moderate environments (such as 33°C), Group B equations would be deemed to be the most appropriate as they rely on less measurements to be taken, which would reduce the risk of measurement error and anomalies in the data impacting on the predicted $T_{es}$.
5. Prior to recommending a final regression model, it is essential that validation of each prediction model with independent databases is required. Under different conditions (clothing, exercise mode, subjects, temperature and humidity), the behaviour of $T_{skin\text{-}insul}$ may be modified, and as it is the predominant predictor variable at an $T_a$ of 33°C and above, any change in the relationship between $T_{es}$ and $T_{skin\text{-}insul}$ will affect the integrity of each equation.

A comparison of equations in groups A to D at a $T_a$ 30°C and 40°C, using independent data sets (data not used in the formulation of the prediction models) was made (Chapter Four) to establish the best prediction model for use in a commercial monitor.

### 3.5 SUMMARY OF FINDINGS AND FUTURE DIRECTION

From the analyses conducted in Section 3.2-3.5, it may be concluded that prediction of $T_{es}$ to an acceptable accuracy was possible during an increasing exercise protocol, using a range of physiological and physical measures. The degree of accuracy depended upon the variables that were included in the regression analysis and the $T_a$ at which the data were collected. The analyses that were conducted established three key points, which identified the need for further research:

1. It was established within this chapter that the collection of data from individual subjects under the same study conditions, and analysing the data in a single analysis was not as accurate as using individual regression equations, but created a more practical means of predicting $T_{es}$. The prediction models that were developed, using multiple linear regression modelling, were able to predict $T_{es}$ to a level deemed to be accurate enough to be both practical for maximal productivity, yet mindful of safety, with a small margin for error. These models were only considered to be valid predictors of $T_{es}$ under the study conditions upon which they were derived. To assess the ability of the prediction models to predict $T_{es}$, further investigations requiring the prediction models to be applied to independent database were required. When these analyses were performed, it was essential that the most precise model be identified, for potential inclusion in a personal heat strain monitor. The preferred prediction model may then be inserted into physiological strain indices, to assess the how the level of error may impact on these indices (Chapter Four).
2. At an individual level, the ability to predict $T_{es}$ was very high when using individual regression models and a range of predictor variables. Individual equations resulting from the simple linear regression analyses were dissimilar

in slope and intercept, and a variety of predictor variables were used to develop the optimal models in the multiple linear regression analyses. Utilising separate models for individuals is not functional for use in a commercial monitor, as the practicality of determining and implementing the model outweighs the advantage of using this technique. Furthermore, it could not be established whether an individual would have the same physiological responses in different situations, or even under identical circumstances. Therefore, even if an individual calibration and regression model was developed, it is uncertain whether this would be valid in a different exercise/work session. Although not practical from a commercial perspective, it would be a valuable tool to understand whether $T_{skin-insul}$ responded the same way in identical situations, on the same person. This would need to be examined in a repeated-measures study design, where the dependant variable was not expected to impact, or to have only minimal impact, on the validity of the measurements recorded (predictor variables and $T_{es}$).

3. With the exception of data collected at 25-27°C, $T_{skin-insul}$ was the most powerful single predictor of $T_{es}$. Several issues need to be resolved prior to the acceptance of $T_{skin-insul}$ as a universal surrogate predictor of $T_{es}$ and suitable for use in a personal monitoring system, at $T_a$ of greater than 30°C. These would include within-subject variance, the effect of clothing, different exercise types, and local skinfold thickness.

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# CHAPTER 4. VALIDATION OF PREDICTION EQUATIONS

An accurate prediction of core temperature ($T_c$) is essential to the precision of a personal heat strain monitor. In Chapter three, four groups of equations were developed to predict thermal strain during exercise on the basis of predicted changes in oesophageal temperature ($T_{es}$). These prediction equations were developed using data collected in 53 trials, across a 15°C air temperature ($T_a$) range (25-40°C). These prediction equations had a standard error of the estimate ($S.E.E._y$) of 0.20-0.35°C, and explained 0.39-0.82 of the proportion of variability in $T_{es}$. The aim of this chapter was to validate these prediction equations, and to assess their suitability for use as physiological strain indices.

Three steps were considered in the validation process of the prediction equations. First, a descriptive analysis of the prediction equations, using the data from which they were developed, was performed to identify any strengths, weaknesses, or irregularities of each equation. Second, each equation was applied to independent databases to assess the validity of each prediction equation under other experimental conditions. Third, the accuracy of the prediction equations for use with recommended heat strain guidelines and physiological strain indices was assessed to ascertain the suitability for substitution into physiological strain indices, for personal physiological monitoring. These steps form the central focus of this chapter.

## 4.1 DESCRIPTIVE ANALYSIS OF PREDICTION EQUATIONS USING DATABASES FROM WHICH THE EQUATIONS WERE DERIVED

In determining the superior prediction equations within Chapter Three, the regression statistics were the only variables taken into consideration. These statistics could not illustrate any differences that were related to the measured $T_{es}$, and if the relationship may have been affected by changes in measured $T_{es}$. Therefore the aim of this section was to provide a descriptive analysis of the relationship between measured $T_{es}$ and predicted $T_{es}$, which enabled further examination of each prediction model.

### 4.1.1 Methods

The measured $T_{es}$ and predicted $T_{es}$ for each equation were plotted as the x and y variables respectively. The residuals (difference between measured and predicted $T_{es}$) were plotted against the measured $T_{es}$ to assess if any trends were evident in the accuracy of the equations, *i.e.* did the accuracy of the equations change as the measured $T_{es}$ changed. A negative residual represented under-prediction of the measured $T_{es}$, and a positive residual indicated over-prediction of measured $T_{es}$. The regression statistics in Figures 3.13 and 3.14 and descriptive statistics were used to support visual observations.

### 4.1.2 Results and discussion

#### 4.1.2.1 Database One (Data collected at 25-27°C)

Four prediction equations were used to analyse data collected in a 25-27°C environment. There were differences observed in the predicted $T_{es}$ values of the four prediction equations, and these differences are highlighted when considered in conjunction with the measured $T_{es}$ (Figure 4.1). The findings may be summarised as follows:

1. The relationship between the measured and predicted $T_{es}$ was not 1:1 for any equation, based on the line of best fit through the data and its relationship with the line of identity. Instead the measured $T_{es}$ changed at a ratio from approximately 1.5:1 (Equation C-25) up to 3:1 (Equation A-25) with the predicted $T_{es}$. For example, in Equation C-25, for a 1.0°C change in predicted $T_{es}$, there was a 1.5°C change in measured $T_{es}$. This indicated that the predicted temperature when using only $T_{skin\text{-}insul}$ to predict $T_{es}$ was less responsive to changes in the measured $T_{es}$, than when the prediction model included multiple predictor variables.
2. Across all equations, as the measured $T_{es}$ increased, the residual values became less positive and closer to zero, indicating that the level of over-predication by the equation was decreasing. At a measured $T_{es}$ of 37-38.5°C, the residual values tended to became negative indicating under-prediction.
3. Data points separate from the main cluster of data were observed, and it was

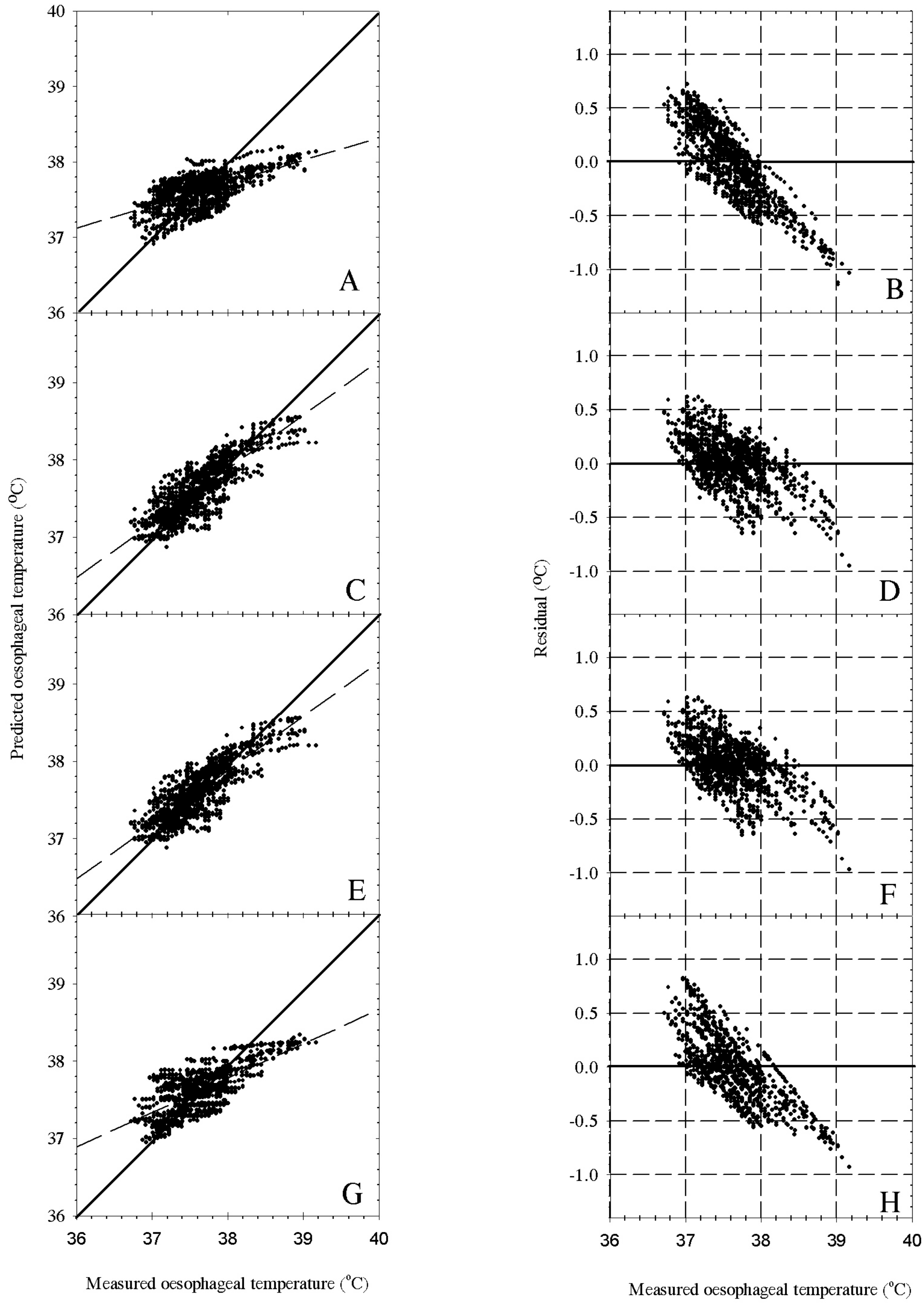



**Figure 4.1:** Relationship between measured and predicted oesophageal temperatures for prediction equations developed at an air temperature of 25-27°C. Graphs A and B = Equation A-25; Graphs C and D = Equation B-25; Graphs E and F = Equation C-25; Graphs G and H = Equation D-25. Solid line equals line of identity. The dashed line equals line of least squares best fit. Residual is the difference between the measured and predicted oesophageal temperature. Refer to Appendix A for details of each equation.

noted that due to the progressive and linear directions of these data points, that they were from the same subject. If this assumption is correct, the predicted $T_{es}$ were only close to the measured $T_{es}$ at the mid point in the range of measured $T_{es}$ during a trial, at approximately 38.0-38.5°C, which is the temperature that heat strain guidelines do not recommend exceeding in industry.

4. Across all equations, the majority of the predicted $T_{es}$ values were within 0.5°C of the measured $T_{es}$, with outlying values in all equations extending to -1.0°C or higher in all models. The $S.E.E._y$ was lower by 0.05-0.10°C in Equation B-25 and C-25 compared to Equations A-25 and D-25, indicating these were more accurate prediction models. Visually, based on the residual plots, Equation D-25 appeared more accurate than A-25, but less accurate than B-25 and C-25. The proportion of data points close to the zero residual line became greater as the measured $T_{es}$ became higher. This has a practical significance since these temperatures are considered more critical to be accurate.

5. These analyses highlight the inadequacies of using only $T_{skin\text{-}insul}$ to predict $T_{es}$ at a lower $T_a$. The result may have occurred because the $T_{skin\text{-}insul}$ response was affected by $T_a$, and this resulted in a dampened $T_{skin\text{-}insul}$ response to changes in $T_{es}$. These results suggest that the insulation was inadequate at this $T_a$. The inclusion of $f_c$ reduced this dampening effect, and further improved the prediction equations, resulting in a minimal role of $T_{skin\text{-}insul}$ in the prediction of $T_{es}$ in Equations B-25 and C-25 (Appendix A). The regression statistics support the notion that $T_{skin\text{-}insul}$, even when combined with $f_c$, is a poor predictor of $T_{es}$ at an $T_a$ of 27°C and below. Therefore it is not appropriate to use these prediction equations at a $T_a$ below 27°C.

#### 4.1.2.2 Database Two (Data collected at 33°C)

Equations used to predict $T_{es}$ in Database Two, showed some characteristics similar to those in Database One, but were more accurate as indicated by the regression statistics. The graphical depiction of the relationship between measured and predicted

$T_{es}$ is observed in Figure 4.2 and key points are summarised below:

1. The relationship between the change in measured and predicted $T_{es}$, based on the line of best fit with the line of identity, was between 1.25:1 and 1.5:1, indicating that the predicted $T_{es}$ was less responsive to the change in measured $T_{es}$. However, the level of response was similar between equations incorporating multiple predictor variables.
2. Data points lying outside the main cluster of data were suggestive of being individual trials, and were observed in all prediction equations at an $T_a$ of 33°C. This trend was present in all equations and occurred at measured $T_{es}$ values less than 37.0°C and higher than 38.0°C. Below a measured $T_{es}$ of 37°C, a large change in the predicted $T_{es}$ was observed for a negligible change in the measured $T_{es}$ for all equations except Equation C-33. It was most apparent in Equation D-33, and approximately 0.75°C change in predicted $T_{es}$ was observed for a 0.1°C change in measured $T_{es}$. It is suggested that this large increase is due to the $T_{skin\text{-}insul}$ measurement adjusting to the increase in skin and air temperature following transfer from a cool room ($T_a$ = 22°C) to the warm climate chamber. This illustrates how the relationship between $T_{es}$ and $T_{skin\text{-}insul}$ is affected by the $T_a$.
3. At a measured $T_{es}$ of 37-38°C, the residual values were evenly distributed around the zero residual line, and were typically within 0.5°C of the measured $T_{es}$ across all equations. At a measured $T_{es}$ of 38°C and above a clear trend of under-prediction was evident, the level of which increased, as the measured $T_{es}$ increased. This under-prediction may result from a lag in the response of $T_{skin\text{-}insul}$ to changes in $T_{es}$, which may be rapidly rising at this time if the heat stress is uncompensable.

#### 4.1.2.3 Database Three (Data collected at 40°C)

Marked differences were observed between the predicted $T_{es}$ values derived from equations developed at an $T_a$ of 40°C (Figure 4.3), with many of the observations made at lower $T_a$ being relevant to these equations. The observations applicable for this higher $T_a$ are highlighted below:

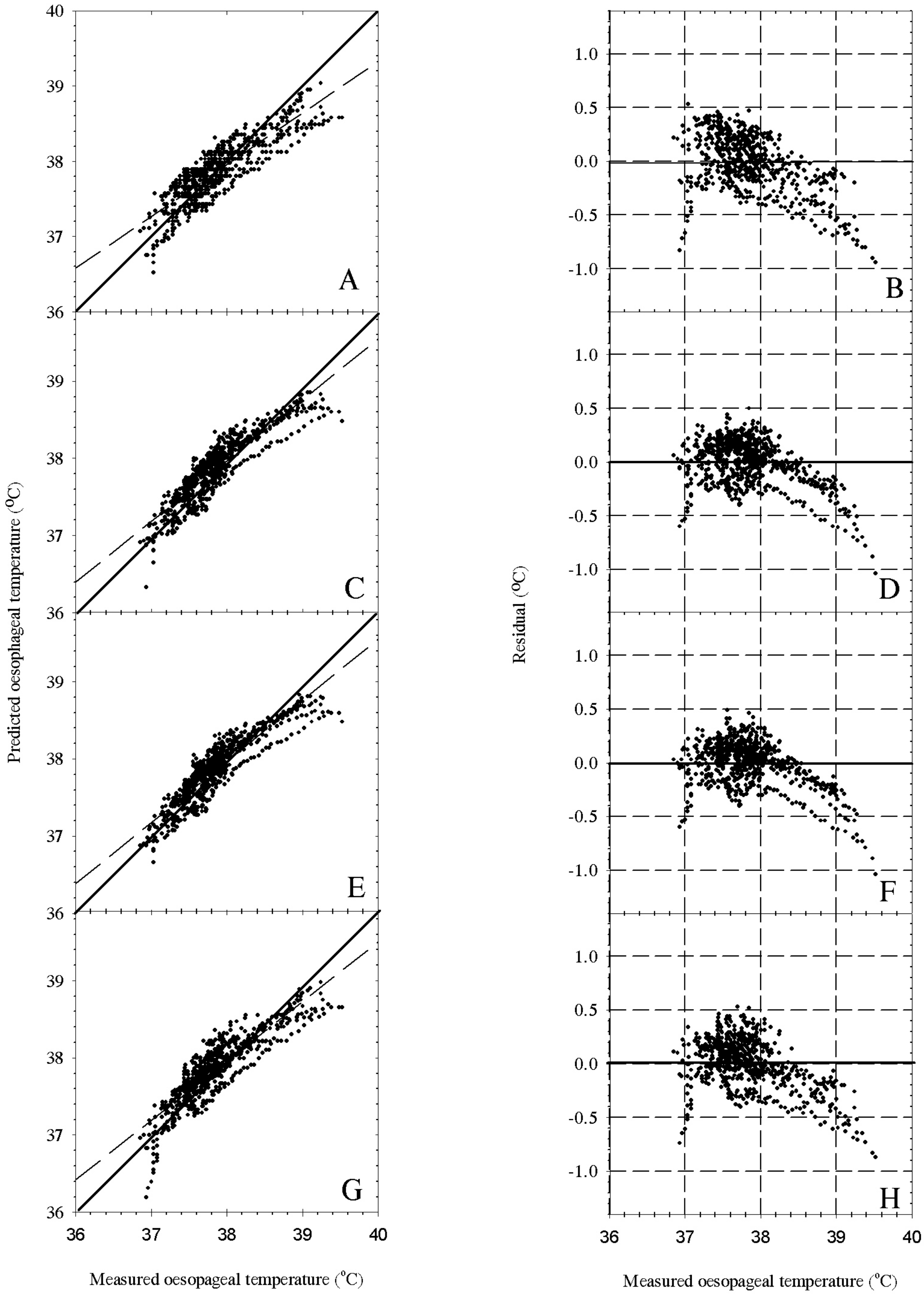



**Figure 4.2:** Relationship between measured and predicted oesophageal temperatures for prediction equations developed at an air temperature of 33°C. Graphs A and B = Equation A-33; Graphs C and D = Equation B-33; Graphs E and F = Equation C-33; Graphs G and H = Equation D-33. Solid line equals line of identity. The dashed line equals line of least squares best fit. Residual is the difference between the measured and predicted oesophageal temperature. Refer to Appendix A for details of each equation.

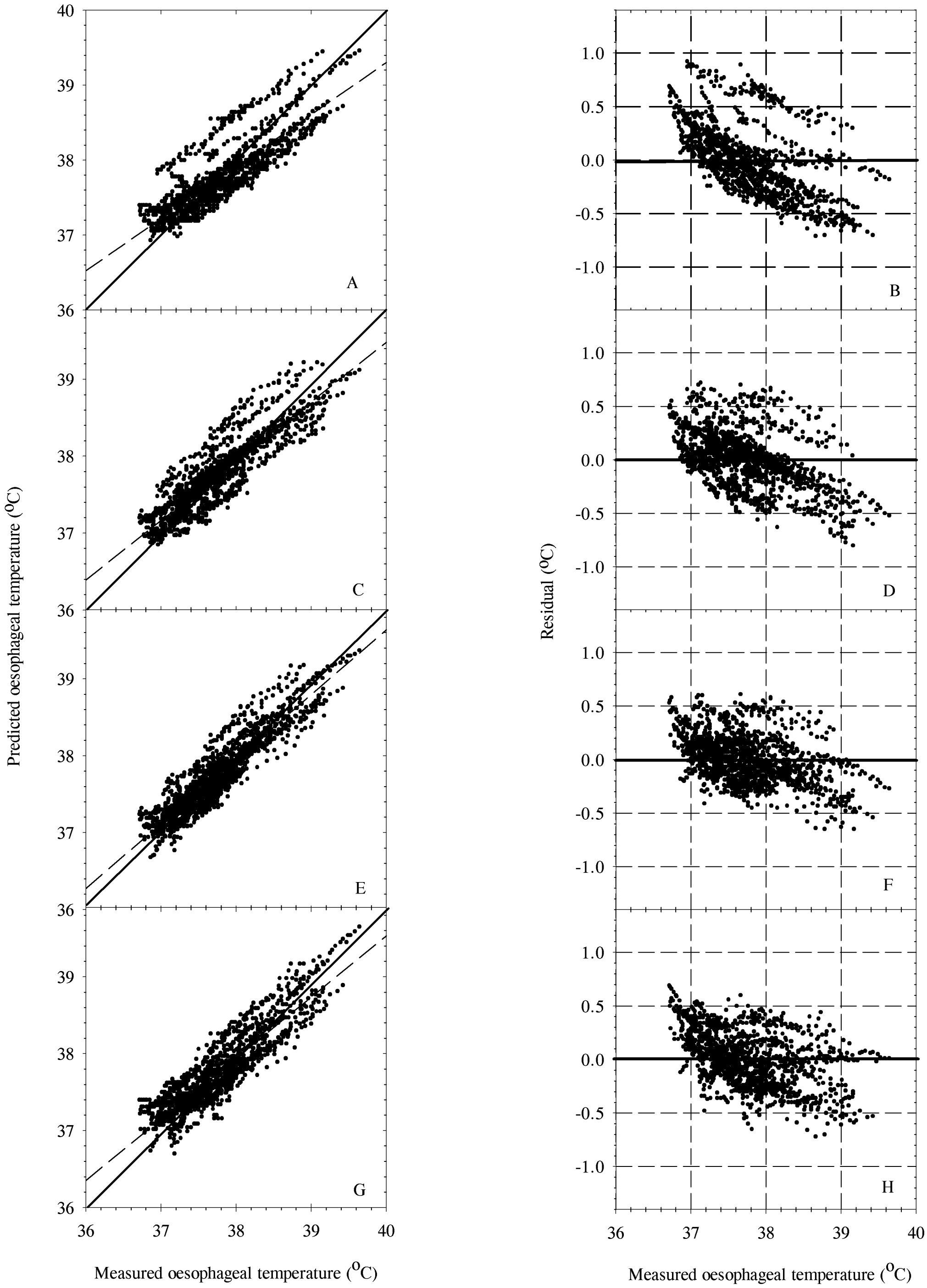



**Figure 4.3:** Relationship between measured and predicted oesophageal temperatures for prediction equations developed at an air temperature of 40°C. Graphs A and B = Equation A-40; Graphs C and D = Equation B-40; Graphs E and F = Equation C-40; Graphs G and H = Equation D-40. Solid line equals line of identity. The dashed line equals line of least squares best fit. Residual is the difference between the measured and predicted oesophageal temperature. Refer to Appendix A for details of each equation.

1. The change in measured $T_{es}$ relative to predicted $T_{es}$ ranged from approximately 1.5:1 to 1.2:1 in Equations A-40 and C-40 respectively. Similar to the analyses at lower $T_a$, these analyses demonstrated that predicted $T_{es}$ did not change at the same rate as measured $T_{es}$. However these equations were closer to the line of identity than those developed at lower $T_a$.
2. Data points that appeared to correspond to single trials and were segregated from the main cluster of data points were observed for each prediction equation. These lines were clearest in Equation A-40 at all measured $T_{es}$, and were also observed above 38.0°C in all other equations. This demonstrates how additional predictor variables were able to increase the accuracy of the models in individuals who may otherwise have large errors in the predicted $T_{es}$.
3. Across each equation there was a trend for data to be over-predicted at lower measured $T_{es}$, and for data to become closer to or below the zero residual line as the measured $T_{es}$ increased. There were still data points over-predicted at a measured $T_{es}$ of 39.0°C, unlike observations at lower $T_a$, where all values at this measured $T_{es}$ were under-predicted.
4. The level of under-prediction was similar across all equations with residual measurements equalling up to -0.8°C across all equations. Large differences in the level of over-prediction between equations was observed, and in Equation A-40, the positive residual extended to 0.9°C. This was 0.6-0.7°C in Equation B-40, C-40 and D-40. The equations showing the lower positive residuals were those that used additional measurements to $T_{skin\text{-}insul}$. This highlighted the role of additional predictor variables in reducing the error of the prediction models.
5. Equation C-40 was considered the most accurate equation as the $S.E.E._y$ attained the upper threshold of 0.20°C. This was visually observed as the distribution of data points around zero was more closely concentrated in this equation than in the other equations, especially at a measured $T_{es}$ of 37.0-38.5°C.

### 4.1.3 General conclusions

The visual and statistical analyses revealed that subtle differences between the equations existed, with unique observations at each $T_a$. The key observations that were made relevant to the prediction of $T_{es}$ when using $T_{skin\text{-}insul}$ are summarised below:

1. Across all equations, there was a trend towards under-prediction of $T_{es}$ at higher measured $T_{es}$, with over-prediction occurring at lower measured $T_{es}$. One theory for this observation is that this trend was the result of $T_{es}$ increasing at a high rate towards the end of a trial, and a lag and blunted response being observed in the $T_{skin\text{-}insul}$ response. The linear modelling of these equations could not account for these changes, and use of a linear model may have resulted in the initial over-prediction that occurred. It was observed that the significant under-prediction occurred at a predicted $T_{es}$ of 38.0°C and above (dependant upon the equation), thus the prediction equations are considered most accurate prior to this point. This pattern was most apparent in the regression equations developed on data collected at a $T_a$ of 33°C. The data shows that an alternative type of modelling (*e.g.* curvilinear) which adjusts for lag in the measurements may be required beyond 38.0°C. Alternatively another linear equation may be used above a predicted $T_{es}$ of 38.0°C in data collected at an $T_a$ of 40°C.
2. The subject characteristics of mass and sum of skinfolds had a significant effect on the prediction model at an $T_a$ of 40°C, as they reduced the $S.E.E._y$ to an acceptable level in Equation C-40. The effect of subject characteristics on the prediction of $T_{es}$ should be observed as a change in the offset between the measured and predicted $T_{es}$. They should not alter the offset within a trial as they remain stable, while $T_{skin\text{-}insul}$ and $f_c$ will vary. Based on the regression coefficients, the sum of skinfolds was the most significant predictor variable, with mass contributing negligible amounts to the prediction equation (but making statistically significant differences). The sum of skinfolds requires further assessment to establish its role in prediction of $T_{es}$ and the relationship with $T_{skin\text{-}insul}$. The regression equations indicated that the role of subject characteristics in the prediction of $T_{es}$ below an $T_a$ of 40°C was minimal, and

the use of the additional measurements does not add significantly to the prediction model.

To examine if the equations may be valid in other situations (individuals and environmental conditions) it is considered essential that the prediction equations are applied to data that is different to that from which the equations were developed. This would enable the validity of the prediction equations under different environmental conditions to be assessed. This was considered the next phase of this project.

## 4.2 USE OF PREDICTION EQUATION IN INDEPENDENT DATABASES

To evaluate the validity of the prediction equations under different experimental conditions, each equation was tested using data not used in their development. That is, each equation was evaluated against an independent data set. Two studies that were recently completed in our laboratory (Taylor *et al.* 2001; Fogarty 2002) contained all measurements required for evaluating the prediction models developed for moderate-to-high $T_a$ and were therefore used for these analyses (Table 4.1).

### 4.2.1 Method

The prediction equations developed at an $T_a$ of 33°C and 40°C were used to predict $T_{es}$ in the data of Taylor *et al.* (2001) and Fogarty (2002) respectively. The relationship between measured and predicted $T_{es}$, and difference between these values (residuals) were plotted, enabling a descriptive analysis of the accuracy of the predicted $T_{es}$. The accuracy of the predicted $T_{es}$ in relation to the measured $T_{es}$ was assessed by calculating the proportion of explained variability and $S.E.E._y$ values for each individual trial. A One-Way Analysis of Variance (ANOVA) for repeated measures was performed on the proportion of explained variability and $S.E.E._y$ values obtained from each database to determine if the equations were significantly different in their level of accuracy.

**Table 4.1:** Characteristics of independent databases

| Database | Air temperature | Clothing | Ergometer | Trial duration | Number of subjects / trials |
|---|---|---|---|---|---|
| **Taylor *et al.* (2001)** | 30°C | Fire fighter uniforms | Step / treadmill | 107 min | 7 / 5 |
| **Fogarty (2002)** | 40°C | Fire fighter uniforms/ minimal | Recumbent cycle | 60 min | 5 / 2 |

### 4.2.2 Results and discussion

#### 4.2.2.1. Analysis of equations for warm conditions (30-36°C)

Figure 4.4 demonstrates the relationship between measured and predicted $T_{es}$ using equations developed on data collected at 33°C that were applied to the data of Taylor *et al*. (2001). The primary observations are as follows:

1. The principal difference observed between each equation in Figure 4.4 was the cluster separate to the main group of data when Equation A-33 and D-33 were used to predict $T_{es}$. The segregation of these data points was less obvious when equations B-33 and C-33 were applied to the same data, indicating the role of $f_c$ in the prediction of $T_{es}$.
2. Examination of the residual analysis indicated a trend for under-prediction of $T_{es}$ at higher measured $T_{es}$. The level of under-prediction (negative residuals) was similar between Equations A-33 and D-33 (-1.4°C and-1.6°C respectively) and Equations B-33 and C-33 (-1.1°C).
3. The peak level of the over-prediction was greater than 1.0°C in all equations, and differed by only 0.10°C between all equations. It was observed that over-prediction of the measured $T_{es}$ was more likely to occur at a lower measured $T_{es}$ across all equations. At a measured $T_{es}$ of 37°C there were data points indicating under-prediction by 0.5°C which was not observed in the data on which the equations were developed.
4. When compared with the data on which the equations were developed (Figure 4.2), the over-prediction of the residuals was more than 0.5°C higher, and the $S.E.E._y$ was greater by up to 0.2°C (compared with each equation in Figure 3.11).
5. In the analysis of the statistics, it was evident that all the equations were poor at accounting for the proportion of explained variance, as the $r^2$ values ranged between 0.46-0.52 (Table 4.2). The $S.E.E._y$ values were also equally high across each equation, and were twice the recommended standard ranging from 0.43-0.45.

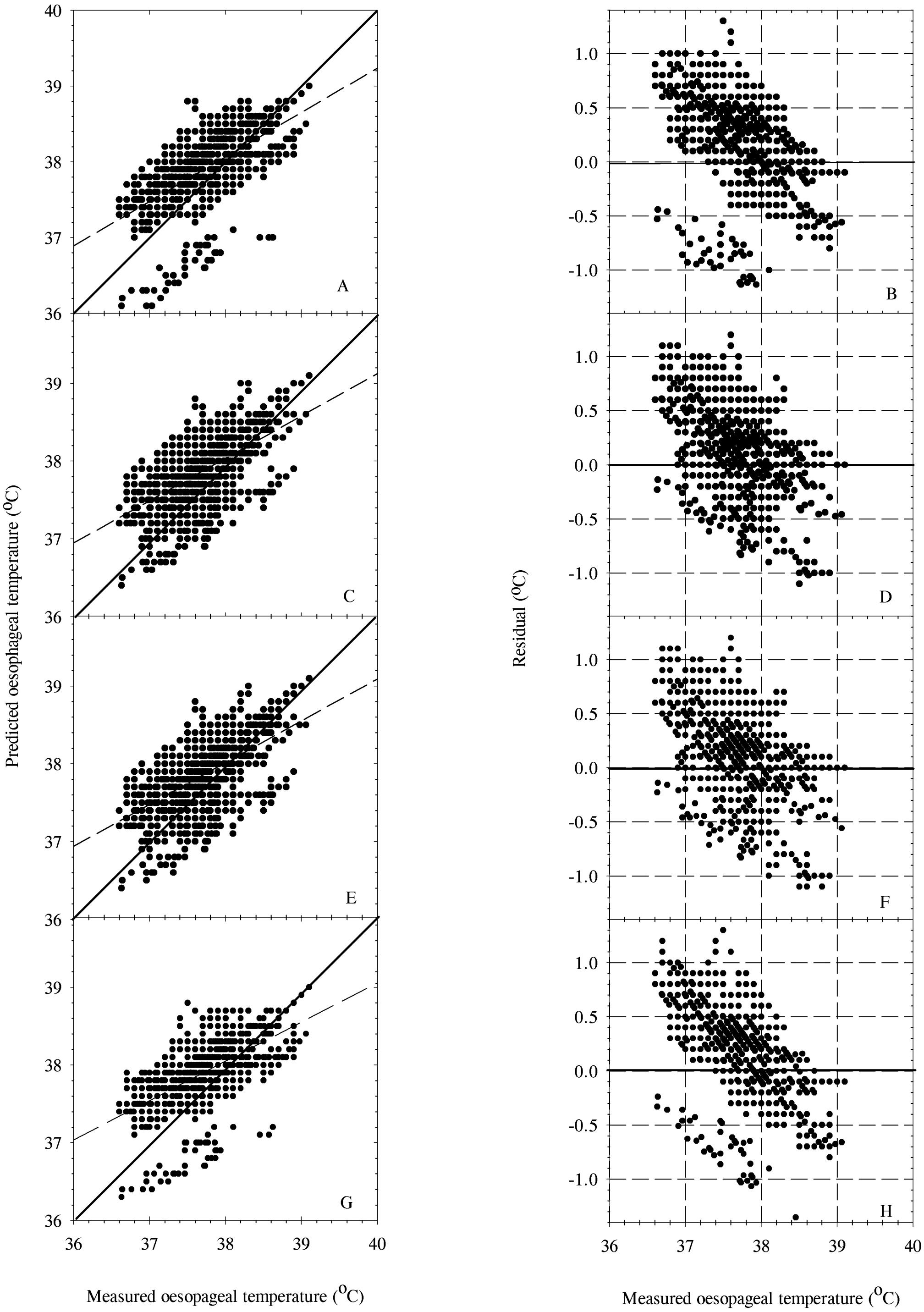



**Figure 4.4:** Examination of the relationship between measured and predicted oesophageal temperatures for prediction equations developed at an air temperature of 33°C applied to Taylor *et al* (2001) database. Graphs A and B = Equation A-33; Graphs C and D = Equation B-33; Graphs E and F = Equation C-33 Graphs G and H = Equation D-33. Solid line equals line of identity. The dashed line equals line of least squares best fit. Residual is the difference between the measured and predicted oesophageal temperature. Refer to Appendix A for details of each equation.

**Table 4.2:** Variability of $T_{es}$ explained by the prediction model, and standard error of the estimate for eight prediction equations

| **Database** | **Equation** | **Proportion of explained variance in $T_{es}$** | **Standard error of the estimate (°C)** |
|---|---|---|---|
| **Taylor *et al.* (2001)** | A-33 | 0.52 | 0.44 |
| | B-33 | 0.47 | 0.45 |
| | C-33 | 0.46 | 0.45 |
| | D-33 | 0.51 | 0.43 |
| **Fogarty (2002)** | A-40 | 0.85 | 0.26 |
| | B-40 | 0.82 | 0.28 |
| | C-40 | 0.84 | 0.39 |
| | D-40 | 0.84 | 0.41 |

Abbreviations: $T_{es}$ = Oesophageal Temperature. Refer to Appendix A for details of the prediction equations.

#### 4.2.2.2 Analysis of equations for hot conditions (40°C)

Many similarities in prediction values were observed in the data of Fogarty (2002) when the four prediction equations were applied. The primary observations include the following:

1. In Figure 4.5, data points were observed to run parallel to the line of identity, with equations differing in the degree of offset from the zero residual line. Data points that were outlying in Equations A-40 and B-40 were merged with the main data set in Equations C-40 and D-40, and were positioned closer to the line of identity. The line of best fit ran parallel to the line of identity in Equations C-40 and D-40, with a close relationship seen in Equations A-40 and B-40.
2. The majority of the data were over-predicted in all equations as observed in the residual plots (Figure 4.5). In all equations, the level of over-prediction extended to 1.1°C. The negative residuals (representing under-prediction) extended to -0.6°C in Equations A-40 and B-40. Equations C-40 and D-40 tracked closely to the zero residual line, and under-predicted the measured $T_{es}$ by up to 0.2°C equally across all measured $T_{es}$.
3. The proportion of variability in $T_{es}$ accounted for by the regression equations was considered high across all equations with values ranging from 0.82-0.85. This indicated that all equations were able to explain a large proportion of the variability in measured $T_{es}$, and the differences between them were inconsequential.
4. When compared with data on which the equations were developed, the proportion of under-prediction was less than that observed in Figure 4.3 by 0.05-0.20°C. However the level of over-prediction was increased by up to 0.5°C, indicating a different distribution of the values.
5. The $S.E.E._y$ values that were obtained varied markedly between equations (Table 4.2). The mean value for each equation ranged between 0.26- 0.41°C. Equation C-40 and D-40 were the most inaccurate, with outlying values exceeding 1.0°C. Equation A-40 and B-40 were similar in the $S.E.E._y$ with values ranging between 0.25-0.30°C, therefore above the target $S.E.E._y$.

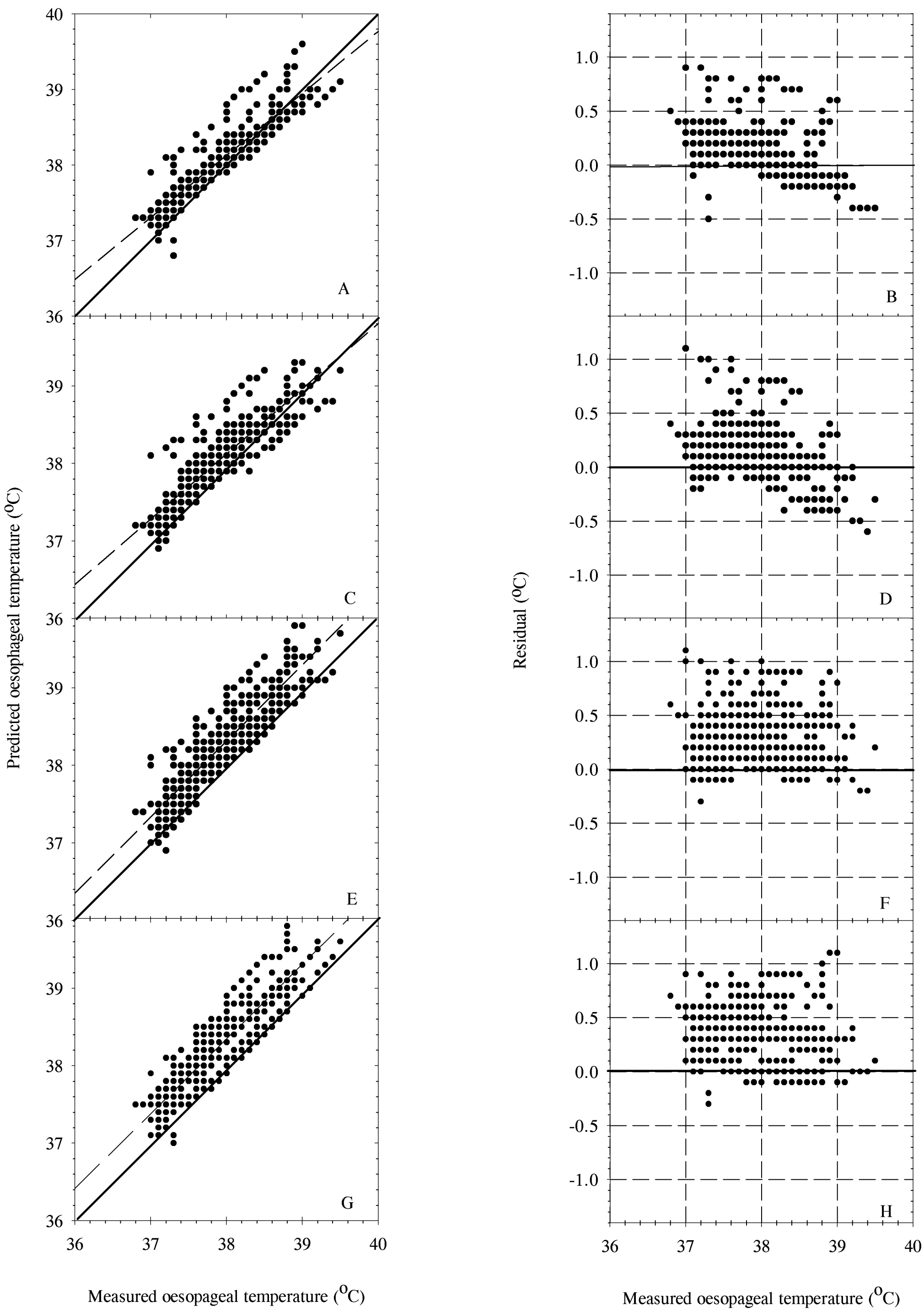



**Figure 4.5:** Examination of the relationship between measured and predicted oesophageal temperatures for prediction equations developed at an air temperature of 40°C applied to Fogarty (2002) database. Graphs A and B = Equation A-40; Graphs C and D = Equation B-40; Graphs E and F = Equation C-40; Graphs G and H = Equation D-40. Solid line equals line of identity. The dashed line equals line of least squares best fit. Residual is the difference between the measured and predicted oesophageal temperature. Refer to Appendix A for details of each equation.

### 4.2.3 General conclusions

A range of interesting observations were able to be made when the equations developed were applied to independent databases including:

1. In the majority of trials across both temperatures, but more so in the Fogarty (2002) database, the proportion of variability in $T_{es}$ that could be explained by the prediction equation was considered very high, and equivalent across all equations. The major between-equation differences that were observed were in the *S.E.E.*$_y$ values. This observation indicates that all prediction equations could track changes in $T_{es}$ acceptably but had greater difficulty in predicting the actual $T_{es}$. On the basis of a lower *S.E.E*$_{.y}$ value, Equation A-40 was deemed to be the equation most suitable for application in a personal heat strain monitor.
2. Based on the regression statistics, the equations applied to the data of Taylor *et al.* (2001) were considered inappropriate as they had high *S.E.E.*$_y$. values that were double the target temperature of 0.2°C. In addition, the proportion of explained variance overall was considered low at less than 0.55. On the basis of this, it is considered equations developed at 33°C are inappropriate for use in a personal monitor to predict $T_{es}$.
3. At an $T_a$ of 40°C, the addition of physical characteristics (Equation C-40), reduced the accuracy of the prediction equation, rather than increasing it as occurred in the development of the equations. When perceived exertion was substituted for $f_c$, the equations became less accurate than the other prediction equations. At an $T_a$ of 40°C, all equations were considered similar and major differences were not observed.
4. It is considered probable that the data is displaying a time lag. This would be considered feasible give that $T_{es}$ and $T_{skin\text{-}insul}$ are not considered to be in direct contact, and are separated by adipose tissue. Furthermore, the $T_{skin\text{-}insul}$ measurement is affected by environmental factors such as high air temperatures, which may precede any changes in $T_{es}$. It is suggested that an investigation of any time lag could provide a means of improving the accuracy of the prediction models.

It is concluded that based on the similarity between the equations in the regression statistics, there was no equation at an $T_a$ of 33°C that was superior at predicting $T_{es}$, and at this stage, all were deemed inappropriate for use in a personal monitor. At a $T_a$ of 40°C, Equation A-40 was superior based on the lower *S.E.E.*$_y$ values found for individual trials. Therefore, due to the simplicity of measuring, at a $T_a$ above 30°C, Equations A-33 and A-40 should be used to predict $T_{es}$. However, based on the group results, there is no equation at a $T_a$ of 30°C and above that would be accurate enough for personal monitoring. It was evident in Section 3.1 that the accuracy of the prediction equations varied according to the actual $T_{es}$, it was considered necessary to further assess the accuracy of the prediction equations in relation to occupational health and safety guidelines for heat exposure and in conjunction with heat strain indices.

## 4.3 USE OF PREDICTION EQUATIONS IN COMBINATION WITH OCCUPATIONAL HEALTH AND SAFETY GUIDELINES

The International Standards Organisation and the National Institute of Occupational Safety and Health (1986) have issued guidelines on the maximum recommended physiological responses that should be elicited during work. These guidelines suggest that a change in $T_c$ of 0.8°C represents a warning phase, with a change in $T_c$ of 1.0°C representing danger. The World Health Organisation (1969) has recommended that deep body temperature should not rise above 38°C during work, however Bernard and Kenney (1994) suggested that this limit be extended to 38.5°C if personal monitoring is used. These target temperatures correspond to a point where a change would take place in the workers behaviour if they were aware of the temperature, whereby they would stop work and remove themselves from the environment causing the elevated predicted $T_{es}$. To be of practical relevance, and to be widely accepted as a means of predicting $T_{es}$, the current prediction equations must be accurate when used with the above guidelines. Therefore, the aim of this section was to determine the efficacy of these equations with respect to changes in $T_{es}$.

#### <u>4.3.1 Method</u>

Two analyses were conducted to examine the accuracy of the prediction equations in predicting the $T_{es}$ deemed unsafe in a working environment. The data used for the analyses were from the databases of Taylor *et al.* (2001) and Fogarty (2002), and had not been used in the development of the prediction equations. Each of the four equations developed at an $T_a$ of 33°C and 40°C were applied to these data.

The first analysis assessed the actual change in $T_{es}$ against a predicted change in $T_{es}$ of 0.8°C and 1.0°C. The measured and predicted $T_{es}$ were converted to change scores, by subtracting the current value for each time point within a trial, from the measurement recorded 10-min from the start of the exercise component of the trial (as $T_{skin\text{-}insul}$ changes rapidly during this time due to the change in conditions). The first point in each trial, where the change in predicted $T_{es}$ equalled 0.8°C and 1.0°C, was found and the change in measured $T_{es}$ at this point was determined and analysed.

The second analysis determined what measured $T_{es}$ related to a predicted $T_{es}$ of 38°C and 38.5°C. Each trial was analysed separately, and the first occurrence of a predicted $T_{es}$ value of 38.0°C and 38.5°C was used for analysis by comparison with the corresponding measured $T_{es}$. A one way-repeated measured ANOVA was used to determine if any significant differences existed between equations.

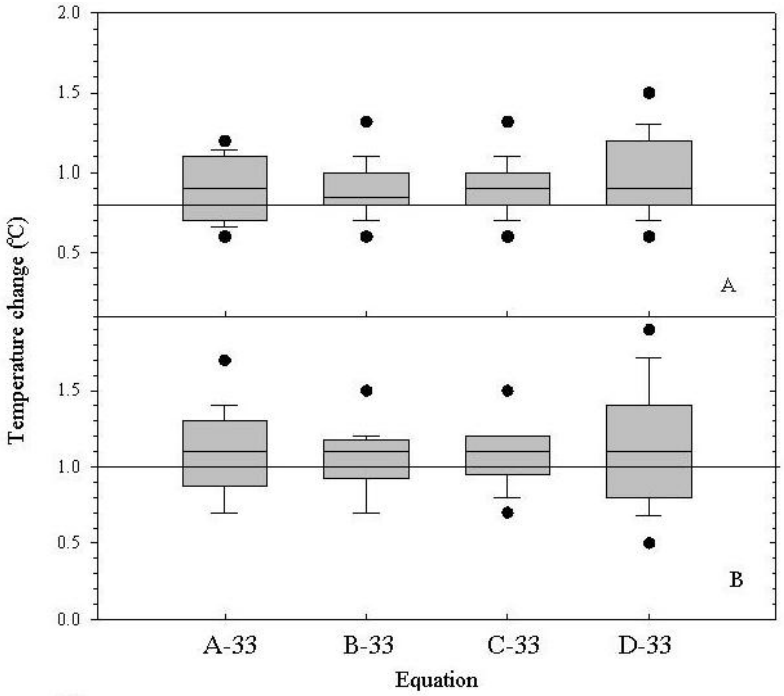
#### <u>4.3.2 Results</u>

##### 4.3.2.1 Prediction of a 0.8°C and 1.0°C change in oesophageal temperature

*4.3.2.1.1 Analysis of equations for warm conditions (30-36°C)*

The summary information (percentiles and outliers) for the change in each equation and database is contained in Figure 4.6, and the interpretations are outlined below:

1. Using the equations developed at 33°C on the data of Taylor *et al.* (2001), it was observed that the prediction equations had a tendency to under-predict the measured change in $T_{es}$. That is, whilst the predicted $T_{es}$ was 0.8°C, the measured change in $T_{es}$ was equal to or greater than 0.8°C in 75% or more of the data in Equations B-33, C-33 and D-33.



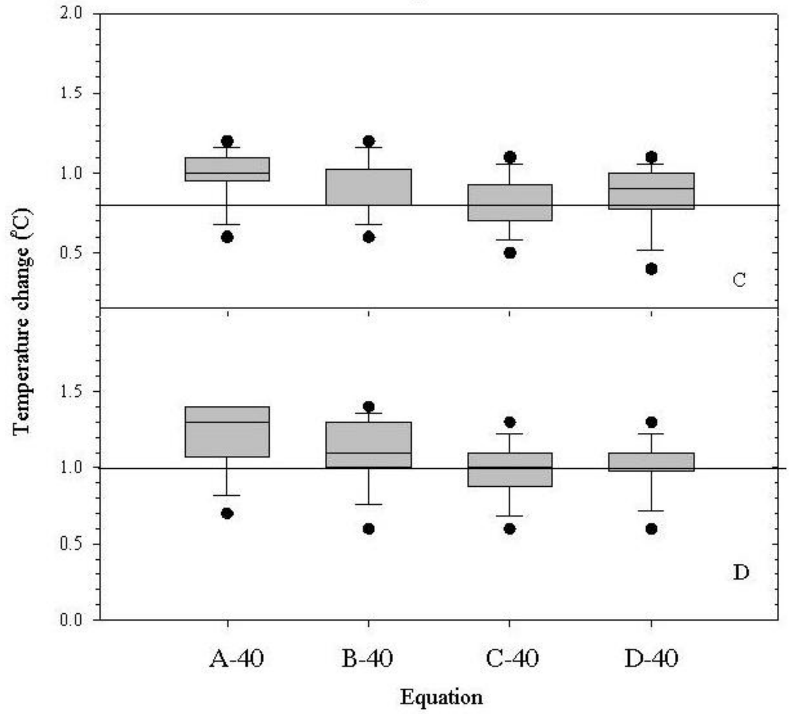




**Figure 4.6:** Summary of relationship between predicted change in oesophageal temperature (0.8° and 1.0°C) and measured change in oesophageal temperature ($T_{es}$) for individual trials. A= Prediction of 0.8°C change in measured $T_{es}$ (Taylor *et al.*, 2001), B = Prediction of 1.0°C change in measured $T_{es}$ (Taylor *et al.*, 2001); C= Prediction of 0.8°C change in measured $T_{es}$ (Fogarty, 2002); D= Prediction of 1.0°C change in measured $T_{es}$ (Fogarty, 2002). Solid line indicates target (predicted change) temperature (0.8° and 1.0°C). Boxes indicate $25^{th}/75^{th\ p}$ percentile rankings. Whiskers indicate $10^{th}/90^{th}$ percentile, middle line represents median, circles indicate outliers. Refer to Table 3.5 for details of each prediction equation.

2. Equations B-33 and C-33 were more accurate than Equations A-33 and D-33. In these equations, it was observed that 80% of the measured values were between 0.7-1.1°C, compared to 50% of the values in this range for Equation A-33. The outlying values of Equation D-33 extended to 0.7°C higher than the target temperature, with the upper 75$^{th}$ percentile being 0.4°C higher than the predicted temperature of 0.8°C.
3. When a predicted temperature change of 1.0°C was calculated, the measured $T_{es}$ values were 0.1-0.2°C higher than the predicted value, indicating that the prediction equations under-predicted the actual $T_{es}$. A change in predicted $T_{es}$ of 1.0°C resulted in 50-75% of the values being under-predicted when compared with the measured $T_{es}$ across all equations (Figure 4.6 B). The mean and median values of the measured $T_{es}$ corresponding to a predicted $T_{es}$ of 1.0°C were 1.1°C, indicating this was sufficiently accurate for this measurement.
4. The range of measured $T_{es}$ values around the predicted change of 1.0°C were highest in Equation D-33, where the difference between the highest and lowest measured $T_{es}$ values was 1.4°C. There were minimal differences between Equations B-33 and C-33, and these equations were considered preferable to the other equations due to the low range in values around the measured $T_{es}$ change. There was however, no significant differences between the equations ($p = 0.23$).
5. The one-way ANOVA identified that significant difference were observed between the prediction equations ($p<0.05$) in the prediction of a 1.0°C change in $T_{es}$. This difference appeared to be based on the large variation in accuracy between Equation D-33 with the remaining three equations.

*4.3.2.1.2 Analysis of equations for hot conditions (36-40°C)*

Utilising the data of Fogarty (2002) to predict the change in measured $T_{es}$, the following observations were noted:

1. The prediction of a 0.8°C change in $T_{es}$ found measured $T_{es}$ values that were higher than the predicted values, indicating that the prediction equations under-

predicted the actual change in $T_{es}$. The range of values contained in Figure 4.6 demonstrated that the change was over-predicted by 0.4°C (Equation A-40 and B-40) and under-predicted by up to 0.4°C (Equation D-40).

2. Significant differences were found between the equations ($P < 0.00$), with these differences likely to be between Equation C-40 (most accurate), and Equation A-40 due to the distribution of the values around the predicted $T_{es}$.
3. A 1.0°C change in predicted $T_{es}$ was most closely related to a 1.0°C change in measured $T_{es}$ in Equations C-40 and D-40. A significant difference was found between the equations ($p < 0.01$), and it is likely, based on Figure 4.6D that the difference was between Equations C-40 and A-40, and Equations D-40 and A-40.

**4.3.2.2 Prediction of an oesophageal temperature of 38.0°C and 38.5°C**

When the measured $T_{es}$ associated with a predicted $T_{es}$ of 38.0°C and 38.5°C was determined, the following observations were relevant for each temperature prediction analysed:

*4.3.2.2.1 Analysis of equations for warm conditions (30-36°C)*

1. The mean measured $T_{es}$ was 0.4-0.5°C less than the predicted $T_{es}$ (Figure 4.7A) for a target $T_{es}$ of 38.0°C for all equations. The distribution of values around the predicted $T_{es}$ value was relatively uniform, and no significant differences between equations were found ($P = 0.48$). Only the 90th percentile and outlying values were above the target temperature for any equation.
2. When a predicted $T_{es}$ of 38.5°C was used as a target temperature, Equations A-40, B-40 and C-40 were similar in the mean and range values. Each of these equations over-predicted the measured $T_{es}$ by an average of 0.4°C, and showed a similar range of values that corresponded to the target predicted temperature. Equation D-40 had a median measured $T_{es}$ value of 38.2°C, 0.2°C higher than the other equations, but the range of measured $T_{es}$ around this was greater, with an outlier being 1.1°C below the target temperature.

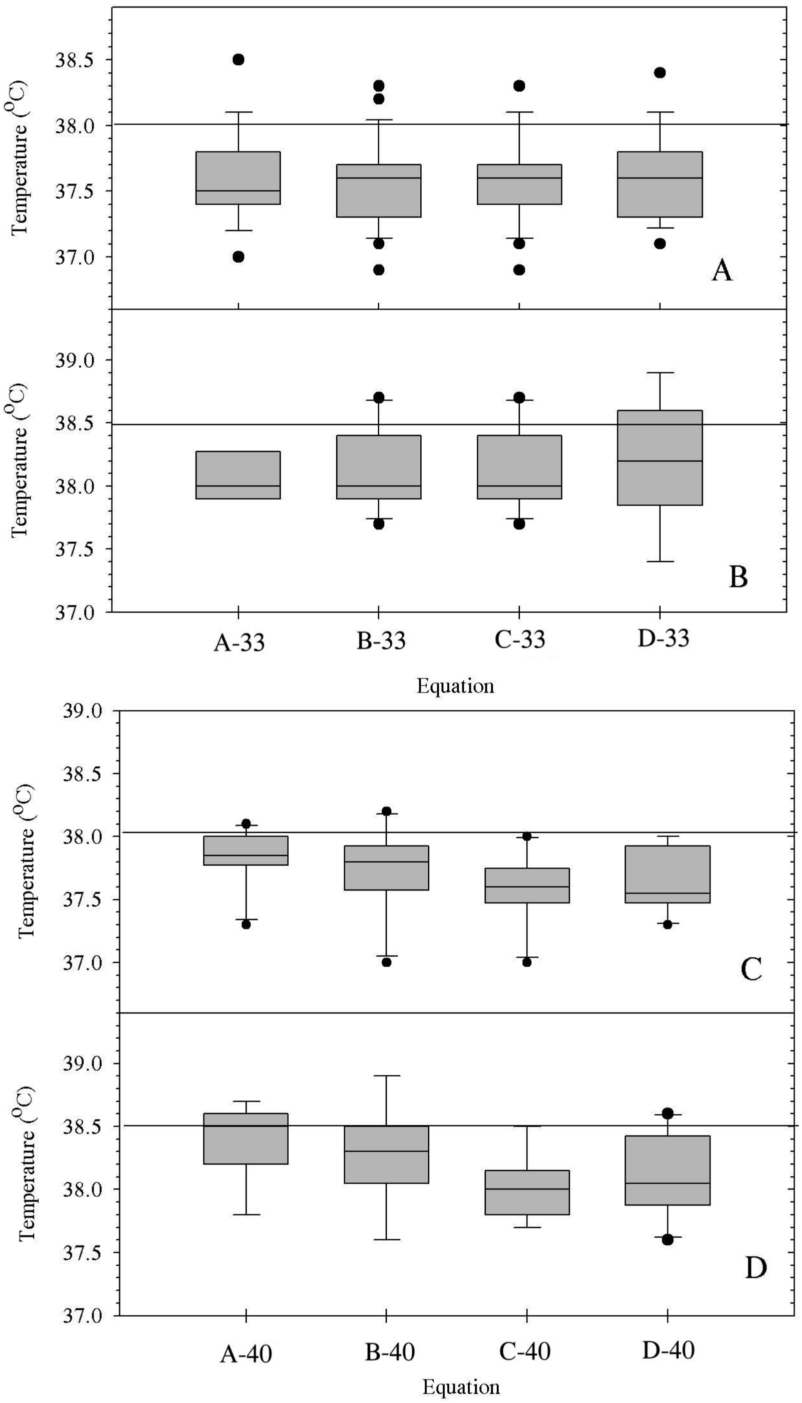



**Figure 4.7:** Summary of measured oesophageal temperature relating to a predicted oesophageal temperature ($T_{es}$) of 38.0°C and 38.5°C for individual trials. A= prediction of 38°C measured $T_{es}$ (Taylor *et al.*, 2001), B = prediction of 38.5°C measured $T_{es}$ (Taylor *et al.*, 2001); C= prediction of 38°C measured $T_{es}$ (Fogarty, 2002); D= prediction of 38.5°C measured $T_{es}$ (Fogarty, 2002) Solid line indicates target temperature (38.0 and 38.5°C).Boxes indicate 25$^{th}$/75$^{th}$ percentile for measured oesophageal temperatures related to a predicted oesophageal temperature of target temperature. Whiskers indicate 10$^{th}$/90$^{th}$ percentile, middle line represents median, circles indicate outliers. Refer to Table 3.5 for details of each prediction equation.

The lower 25th percentile was equal across all equations (37.9°C), and the differences between the equations was not significant ($p=0.34$).

*4.3.2.2.2 Analysis of equations for hot conditions (40°C)*

1. At a predicted $T_{es}$ of 38.0°C the median measured $T_{es}$ was 37.6-37.8°C across all equations, with Equations A-40 and B-40 being the most accurate. The outlying values obtained were equivalent in equations A-40 and D-40 (37.3°C), and in Equations B-40 and C-40 (37.0°C).
2. Based on the median, and 25th/75th percentile values (Figure 4.7 C), Equation A-40 was deemed the most accurate as the median value was closer to the target temperature, and the range of values around the target temperature was smaller than the other equations. The differences between equations were significant ($p<0.00$), and based on the means and distribution of the values, this significance was likely to have been between Equations A-40 and C-40, and Equations A-40 and D-40.
3. Prediction of an $T_{es}$ of 38.5°C demonstrated that Equation A-40 was superior, with the median measured $T_{es}$ associated with a predicted $T_{es}$ of 38.5°C being 38.4°C. Equations B-40, C-40 and D-40 had median measured $T_{es}$ values of 38.3°C, 38.0°C and 38.1°C respectively corresponding to a predicted $T_{es}$ of 38.5°C, demonstrating that these prediction equations over-predicted measured $T_{es}$. The level of under-prediction was within 0.2°C of the target temperature across all other equations, but extended up to 0.4°C (Equation B-40).
4. The box plots in Figure 4.6-D revealed that the 25th/75th percentiles for all equations covered a similar range, with the exception of Equation C-40 which was more compact, yet substantially over-predicted the measured $T_{es}$. Significant differences between equations ($p<0.00$) was noted, with this difference likely to be between Equation C-40 and A-40 based on mean values.

### 4.3.3 Data interpretation and conclusions

The prediction equation recommended for use in a personal heat strain monitor would depend on if the actual $T_{es}$ was being measured or the change in $T_{es}$. There was only one significant difference between the prediction equations using the Taylor *et al.* (2001) database, however many significant differences were found in the analyses of Fogarty (2002). It is on the basis of these differences that the decision was made to use different equations for different tasks:

1. If the prediction of a change in $T_{es}$ was required, Equation C-33 and C-40 are recommended;
2. If the prediction of $T_{es}$ was required, Equation A-33 and A-40 are the most accurate models. However, it is noted that equation A-33 was unable to attain the level of accuracy that would be recommended for use in a personal heat strain monitor.

The selection of a different equation for each purpose was based upon the findings that ascertained the superiority of each model under different situations. However, during the analyses two main points were noted, and these are summarised below:

1. It was found that all prediction equations under-predicted the change in measured $T_{es}$, but over-predicted the measured $T_{es}$. The under-prediction of the change in $T_{es}$ may have been expected, based on the relationship between measured and predicted $T_{es}$ In these equations, a greater change in measured $T_{es}$ was observed for a given change in predicted $T_{es}$. Therefore, when a change in predicted $T_{es}$ was found, the change in the measured $T_{es}$ would be higher, giving the impression that the prediction equation under-predicted measured $T_{es}$. This result was unexpected as a rapid increase in $T_{skin\text{-}insul}$ was often observed at the start of exercise, and at lower $T_a$, $T_{skin\text{-}insul}$ may not have equalised with $T_{es}$. To remove this affect, the first 10-min of the data was not used in the analyses. Ths appeared to be effective for most of the studies, however it is observed that in Figure 4.1C, that this did not occur in all trials.
2. When the independent databases were analysed, Equation D-33 and D-40 were deemed inferior to Equation A-33 and A-40. Equations D-33 and D-40 were

initially developed to improve the prediction of $T_{es}$ by incorporating other variables (excluding $f_c$), with $T_{skin\text{-}insul}$ to improve the accuracy of the prediction equation. However, on the independent databases, the accuracy of the equation was not improved by the inclusion of the rating of perceived exertion, mass and sum of six skinfolds. Furthermore, Equations D-33 and D-40 require more complex measurements and supplementary user input. This introduces other potential sources of error into the prediction model. Based on these conclusions, equations D-33 and D-40 were not considered in further analyses.

The next step in the validation process required testing for any significant differences between Equations A-33 and C-33, and A-40 and C-40, using the results of analyses conducted in Section 4.3. These analyses were used to determine if there were any statistically significant differences in the predictive ability of these equations across different equations to predict $T_{es}$. If there was no difference found between the ability of these equations to predict $T_{es}$, Equations A-33 and A-40 would be accepted as the best predictors of $T_{es}$ based on the simplicity of their use and predictive ability of the equations.

## 4.4 STATISTICAL COMPARISON OF GROUP A AND C EQUATIONS USING DATA COLLECTED AT 30°C AND 40°C

In Section 4.3 it was identified that a different prediction equation, requiring different variables to be collected should be used dependant upon the purpose of the analysis. Specifically, if the change in $T_{es}$ was required to be predicted, Equations C-33 and C-40, requiring the measurements of $T_{skin\text{-}insul}$, $f_c$, mass and sum of skinfolds be collected and used to predict $T_{es}$. However, should the actual value of $T_{es}$ be required, only equations using $T_{skin\text{-}insul}$ (Equations A-33 and A-40) should be used. Further analysis was required to assess if there were any statistically significant differences between these equations and to determine if it was necessary to use different equations.

### 4.4.1 Methods

The results of the analysis in Section 4.3 were used to compare any significant differences between Equations in Group A and C. The values that corresponded to a predicted change in $T_{es}$ of 0.8° and 1.0°C, and an $T_{es}$ of 38.0°C and 38.5°C were analysed with a paired T-test to identify if there were any significant differences ($p < 0.05$).

### 4.4.2 Results and discussion

Results indicated that differences were found between the A and C equations (Table 4.3) as indicated below:

1. There were no significant differences between Equations A-33 and C-33 in any of the analyses. The mean values differed by 0.02°C or less, which is considered inconsequential as the lowest measurable unit in this laboratory is considered to be 0.05°C.
2. When the accuracy of the change values was assessed, significant differences existed between Equations A-40 and C-40. Equation C-40 was considered to be significantly more accurate at predicting a 0.8°C and 1.0°C change in $T_{es}$°C.
3. Use of Equation A-40 to predict an $T_{es}$ of 38.0°C and 38.5°C, resulted in measured $T_{es}$ values that were significantly closer to the predicted $T_{es}$ than when using Equation C-40. The differences between the mean values were 0.25°C for a prediction of 38.0°C and 0.40°C for a prediction of 38.5°C.
4. Based on the significant differences between the equations, it was identified that the both types of equations need to be retained for specific purposes. Therefore, if a change in $T_{es}$ is needed to be predicted, Equation C-33 and C-40 should be used. If the actual $T_{es}$ is required to be predicted, Equation A-33 and A-40 is recommended. Should the $T_a$ be expected to not exceed 36°C, then either equation is appropriate for use.

**Table 4.3:** Accuracy of using prediction equations from Group A and C to predict measured oesophageal temperature relating to industrial strain guidelines

| **Equation** | **Prediction of 0.8°C change** | **Prediction of 1.0°C change** | **Prediction of 38.0°C** | **Prediction of 38.5°C** |
|---|---|---|---|---|
| **A-33** | 0.90 (0.04) | 1.06 (0.85) | 37.57 (0.08) | 38.08 (0.08) |
| **C-33** | 0.89 (0.03) | 1.05 (0.04) | 37.55 (0.12) | 38.09 (0.09) |
| **A-40** | 0.99 (0.03) | 1.2 (0.06) | 37.83 (0.05)* | 38.4 (0.08)* |
| **C-40** | 0.82 (0.03)* | 0.97 (0.04)* | 37.59 (0.08) | 38.01 (0.06) |

Note: Data are means and variance. * indicates significant difference ($P < 0.05$).Refer to Table 3.5 for details of each prediction equation.

## 4.5 USE OF PREDICTION EQUATIONS WITH EXISTING HEAT STRAIN INDICES

Four heat strain indices were introduced in Section 2.4. Two of these indices rely on measurements of sweat rate or sweat loss, and are therefore inappropriate for continuous monitoring in practical situations. The remaining two indices were the physiological strain index (PSI) (Moran *et al.* 1998) and the cumulative heat strain index (CHSI) (Frank *et al.* 2001). These indices use direct continuous measurements of $f_c$ and $T_c$ to evaluate the physiological strain. The aim of this section was to establish whether prediction equations A-33 and A-40 could be substituted for measured $T_{es}$ into the heat strain indices. If it is found that the equations be considered sufficiently accurate, there is a significant practical application for the equations since both indices have been shown to be valuable tools to aid in the quantification of thermal strain. If a predicted $T_{es}$ could be used within either index, then both the index and the prediction equation could be incorporated into a heat strain monitor for use in the field.

### 4.5.1 Methods

The PSI and CHSI (equations 2.3[6] and 2.4[7] respectively) were applied to individual trials in the independent databases (Taylor *et al.*, 2001; Fogarty, 2002).The measured or predicted $T_{es}$ (prediction Equations A-33 and A-40) and the direct measurement of $f_c$ were used in these calculations, to derive measured and predicted PSI and CHSI values for each trial. These were analysed using descriptive statistics, with the accuracy of the PSI evaluated further by investigating the range and distribution of the difference between the measured and predicted strain index values. These analyses were also performed on data where the measured PSI was greater than 5.0 (characterising moderate- high physiological strain), to give an indication of whether

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Equation 2.3 $$PSI = 5(T_{ret} - T_{re0}) \cdot (39.5 - T_{re0})^{-1} + 5(HR_t - HR_0) \cdot (180 - HR_0)^{-1}$$

7

Equation 2.4 $$CHSI = \left[\sum_{o}^{t} hb - HR_0 \cdot t\right] \cdot 10^{-3} \cdot \left[\int_{o}^{t} T_{re} \cdot \, dt \ - \ T_{re_o} \cdot t]\right] \text{ (units)}$$

the distribution of residuals was altered at moderate-high levels of thermal strain, and therefore the accuracy of the indices was also altered.

### 4.5.2 Results and discussion

Figure 4.8 demonstrates the relationship between predicted and measured PSI and CHSI. The following observations were made from this figure:

1. In both databases, the PSI and CHSI were over-predicted when Equations A-33 and A-40 were substituted for the measured $T_{es}$ in the indices. In the data of Taylor *et al.* (2001), 27% of the predicted PSI values fell within 0.5 of the measured PSI (Figure 4.9 A), with 82% of the data equal, to or greater than (over-predicting) the measured PSI. The data were clearly negatively skewed in the Taylor *et al.* (2001) analyses, with 29.2% of the values being in the vicinity of 0.5-0.99 of the measured PSI value. Up to 2.2% of predicted PSI values were ±2.0-2.5 different from the measured PSI value.
2. In the analyses of Fogarty (2002), there were clear differences in the distribution of the residuals compared with Taylor *et al.* (2001; Figure 4.9 B). Forty percent of the PSI values were under-predicted, the majority of these being ± 0.5 of the measured value, and with no values under-predicted by more than 1.0. The distribution of the data revealed that the predicted PSI using Equation A-40 was concentrated closely around the measured PSI, with 94% of the values falling within 1.0 of the predicted PSI. When only the data at, or above, a measured PSI of 5.0 were considered, there was no change in the distribution of the values, which differed to Taylor *et al.* (2001; Figure 4.9A and C).
3. In the analyses of Fogarty (2002), at a measured PSI of 5.0 or higher, 48% of the predicted PSI values were negative, indicating under-prediction of the measured PSI (Figure 4.9 B and D). This was a higher percentage than when all PSI values were considered, and was predominantly due to a greater distribution of PSI residuals being under-predicted by 0.5-1.0 (increase of 12.6%).

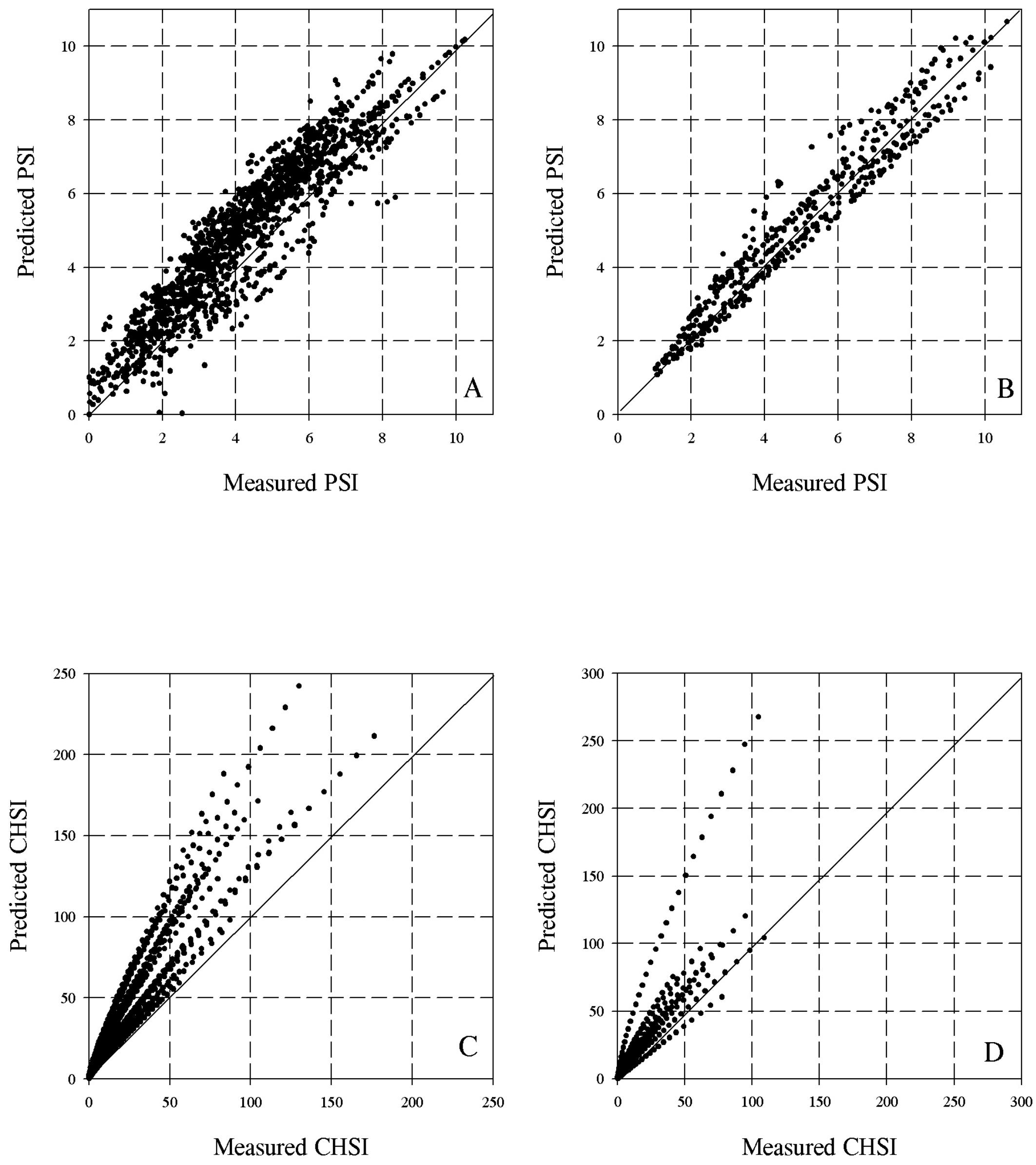


**Figure 4.8:** Relationship between physiological strain indices using measured and predicted $T_{es}$ in independent databases. A= Equation A-33 (PSI; Taylor *et al.*, 2001); B= Equation A-40 (PSI; Fogarty, 2002); C= Equation A-33 (CHSI; Taylor *et al.*, 2001.); D= Equation A-40 (CHSI; Fogarty, 2002). Abbreviations: PSI= Physiological Strain Index; CHSI = Cumulative Heat Strain Index. Solid line indicates line of identity. Refer to Appendix A for details of each prediction equation.

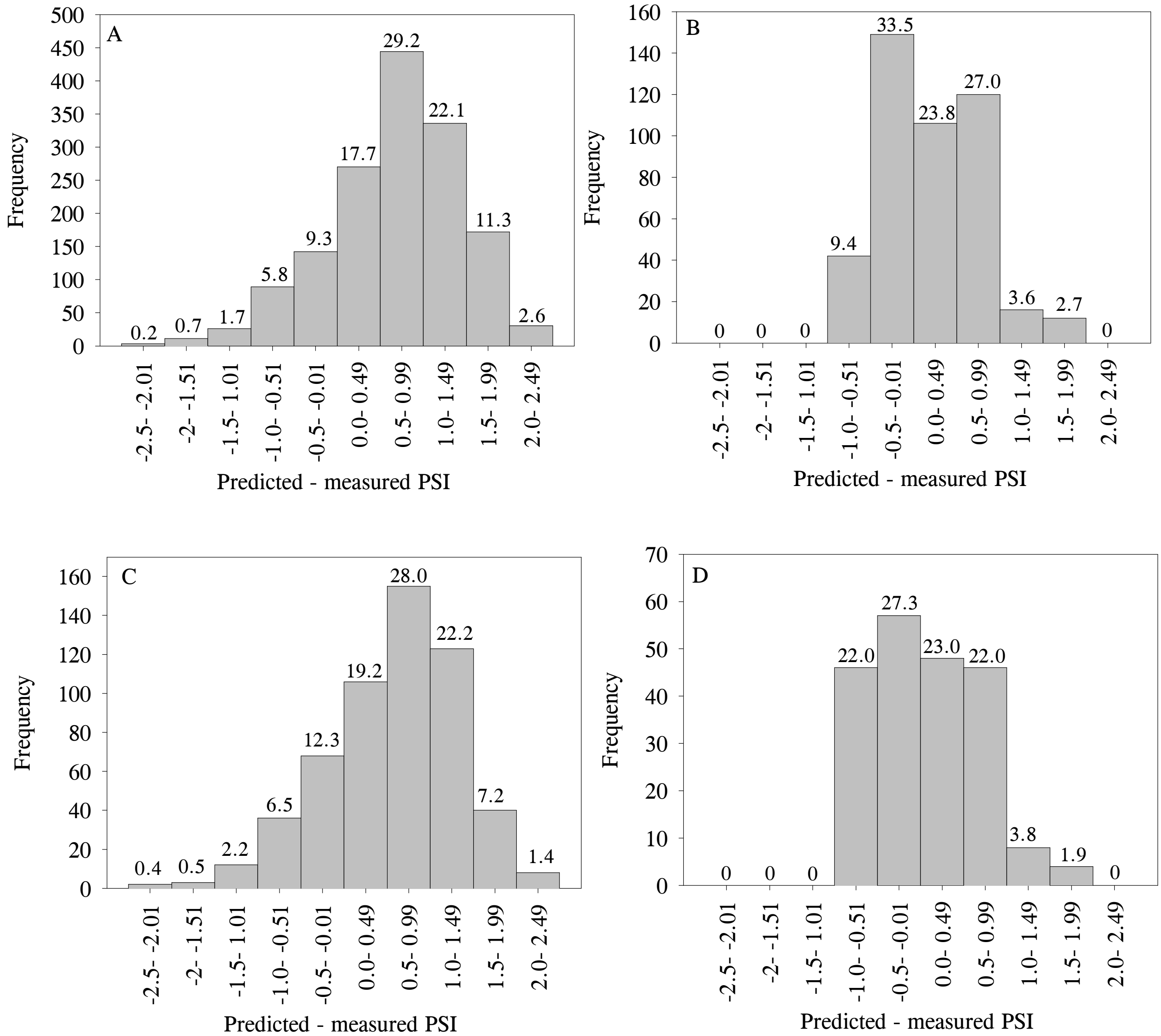


**Figure 4.9:** Distribution of residual PSI values for independent databases. Values are the measured value subtracted from the predicted value. The percentage of the total value in each category is listed at the top of each bar. A: Equation A-33 (Taylor *et al.*, 2001); B: Equation A-40 (Fogarty, 2002); C: Equation A-33 (Taylor *et al.*, 2001) measured PSI values of 5.0 and above; D: Equation A-40 (Fogarty, 2002) measured PSI values of 5.0 and above. Abbreviations: PSI = Physiological Strain Index. Refer to Appendix A for details of each prediction equation.

4. Large differences between the measured and predicted CHSI values were observed, that were not apparent in the PSI analysis (Figure 4.8C and D). The predicted CHSI value was up to 2.3 and 2.6 times the measured CHSI value at the endpoint of exercise in the Taylor *et al.* (2001) and Fogarty (2002) databases respectively. These CHSI values were a maximum of 112 and 163 units different at the end of exercise in the Taylor *et al.* (2001) and Fogarty (2002) databases respectively. As the CHSI is a cumulative index, small differences between the predicted and measured $T_{es}$ were exacerbated when the CHSI was used. It was apparent that the Equations A-33 and A-40 over-predicted $T_{es}$ when the predicted $T_{es}$ was inserted into the CHSI equation, an observation that was not apparent in the PSI analyses. Of particular note in the application of prediction Equation A-33 into the CHSI, was the convex shape of some trials, which demonstrated that the difference between the measured and predicted CHSI was reduced as time progressed. This may be attributed to the under-prediction of measured $T_{es}$ at a higher temperatures, which resulted in less difference between the measured and predicted CHSI at higher strain levels. It is concluded that the use of Equations A-33 and A-40 in the CHSI was not deemed suitable at a $T_a$ greater than 30°C.

### 4.5.3 Data interpretation and conclusions

To consider viable as a commercial heat strain monitor, two main factors must be reviewed. Foremost is the safety of the worker. The second consideration is to maximise productivity. Both of these factors require minimal error in the prediction of the $T_{es}$, with the critical component being that the predicted strain index value has only a small degree of under-prediction compared to the actual strain index value. This requirement was met when prediction Equations A-33 and A-40 were used to predict the $T_{es}$ value in the PSI.

The PSI values that correspond to the maximal recommended industrial exposure limits are 4.0-5.0. The physiological values corresponding to a PSI value of 4.0 or 5.0 are an $T_{es}$ of 38.0°C, and $f_c$ of 115 b·min$^{-1}$(PSI=4.0), or 38.25°C and $f_c$ of 125 b·min$^{-1}$

(PSI=5.0) assuming a resting $T_{es}$ of 37°C and $f_c$ of 70 b·min$^{-1}$.These assumptions are used in the following discussions and in relation to recommended strain guidelines. From the perspective of worker safety, 96.9% of the predicted PSI values at an $T_a$ of 30°C, and 100% of the values above a PSI of 5.0 at an $T_a$ of 40°C, fell within -1.0 of the actual PSI. When these values were considered with the potential error, the maximal measured $T_{es}$ that would be attained should the PSI be under-predicted by 1.0, would have been 38.5-38.75°C, depending upon the recommended maximal PSI level (4.0 or 5.0). These physiological values are lower than the $T_{es}$ that corresponds to heat exhaustion and heat stroke, therefore, the use of Equations A-33 and A-40 are deemed suitable for use in the PSI equation in a heat strain monitor to meet the safety requirements of workers in a $T_a$ of 30-40°C.

The over-prediction of measured $T_{es}$ that was observed in the analyses would affect practical use of the model by causing workers to cease work prior to reaching the recommended physiological limits, due to the monitor showing they had reached the strain limit. This would reduce overall productivity. For example, in the analyses of Taylor *et al.* (2001) it was observed that 14% of the predicted PSI values were ±1.5 outside the measured PSI value. Therefore at a PSI value of 4.0 (predicted $T_{es}$ = 38.0°C), the measured $T_{es}$ could be 37.25°C, which is well below the work termination threshold, and could result in decreased productivity in 14% of the occurrences.

The PSI relies on an accurate measure of initial $T_{es}$, and an accurate assessment of the change in $T_{es}$. The level of strain ascribed is a function of the current $T_{es}$, and its place within the range of basal and maximum $T_{es}$ (39.5°C). Should the basal temperature be accurately known, then Equations C-33 and C-40 may be inserted into the PSI, instead of Equations A-33 and A-40 as they were superior in the detection of a change in $T_{es}$ (Section 4.4). The concept of calibrating the predicted $T_{es}$ to measured $T_{es}$ at the start of an exposure was investigated in Section 3.3. It was found that the accuracy of this method was poorer than using the raw $T_{skin\text{-}insul}$ and change methods, and was therefore not evaluated further. However if an accurate measure of $T_{es}$ could be gained, and combined with the change in $T_{es}$ (Equations C-33 and C-40), then the accuracy of the PSI using predicted $T_{es}$ may be increased.

### 4.6 SUMMARY AND CONCLUSIONS

A descriptive analysis of the relationship between measured and predicted $T_{es}$ in the data upon which the equations were developed, revealed that there was a distinct pattern in the relationship between measured and predicted $T_{es}$, that was similar through all equations. At lower measured $T_{es}$, there was over-prediction of the measured $T_{es}$, with a trend towards under-prediction as the measured $T_{es}$ increased.. This was most readily observed in the equations developed on data collected at an $T_a$ of 25°C and 27°C where the prediction equations were poor at predicting $T_{es}$.

Independent databases (Taylor *et al*, 2001; Fogarty, 2002) assessed the prediction equations developed for data at moderate-high $T_a$. In the data collected at 30°C over-prediction of $T_{es}$ at lower measured $T_{es}$, and under-prediction of $T_{es}$ at higher measured $T_{es}$ was still observed. This pattern was less obvious in the data collected at 40°C with most data being over-predicted by all prediction equations. The inclusion of variables other than $T_{skin\text{-}insul}$ into a prediction model was shown to have little improvement in the proportion of variability in $T_{es}$ that could be explained by the predicted $T_{es}$, but substantially increased the $S.E.E._y$, notably at an $T_a$ of 40°C, thereby decreasing the accuracy of the equations. No equation attained a satisfactory $S.E.E._y$ of 0.02°C, with Equation A-40 being closest at 0.25°C. The $S.E.E._y$ values for the equations developed at 33°C were over two times the recommended value.

Using independent databases, the prediction equations were assessed on their ability to predict temperatures regarded as critical in occupational health and safety guidelines. These temperatures included the ability to predict a $T_{es}$ measurement of 38°C and 38.5°C. Based on the regression statistics equations, all prediction equations over-predicted the measured $T_{es}$, however Equations A-33 and A-40 were recommended for the prediction of $T_{es}$, since these equations were most closely associated with the target measured $T_{es}$. When a change in $T_{es}$ of 0.8°C and 1.0°C were required to be predicted, Equations C-33 and C-40 were the preferred equations as these were considered to be the most accurate. Statistical analysis revealed that there were significant differences between the accuracy of Equations A-33 and C-33, and Equations A-40 and C-40, thereby eliminating the possibility that one model was suitable for all purposes and simplifying the prediction of $T_{es}$ in a personal monitoring system. A personal monitoring system therefore would require workers $f_c$, mass and sum of skinfolds to be known if the monitor was to be used for the purpose of assessing the change in predicted $T_{es}$. The necessity of these measurements would increase the complexity of the initial set-up for each worker and would reduce its appeal to commercial customers.

When the predicted $T_{es}$ was inserted into physiological strain indices (PSI and CHSI) it was found that prediction Equations A-33 and A-40 were suitable for substitution into the PSI, but not the CHSI. Equation A-40 was most accurate with the PSI, where the difference between measured and predicted PSI values were the lowest, with 94% of the values falling $\pm 1.0$ of the measured PSI. There was an expected over-prediction of the predicted PSI and CHSI values, which may be attributed to the measured $T_{es}$ being over-predicted, and the change in $T_{es}$ being under-predicted. The small differences observed between the measured and predicted $T_{es}$ were exacerbated in the CHSI, making small differences of predicted $T_{es}$ into large differences in the CHSI values, thereby making it unsuitable for use with equations to predict $T_{es}$.

To summarise, the use of $T_{es}$ prediction equations as a substitute for measured $T_{es}$ shows a high level of potential. It is most likely to be suitable at higher $T_a$ and in conjunction with a validated heat strain index such as the PSI as the strain measurement does not solely rely on the $T_{es}$ measurement. Should the stated limitations be acceptable, Appendix B summarises the above findings and outlines the practical consideration for development of a heat strain monitor. Further investigation of the role of $T_{skin\text{-}insul}$ as a surrogate index of $T_{es}$ is required to validate the measures under varying situations. From a health and safety perspective, over-prediction is safer than under-prediction, but the large error in over-prediction will affect productivity in the working environment and acceptance of its use. Given the current limitations it is identified that there are many areas requireing further research to improve use of $T_{skin\text{-}insul}$ as a surrogate index of $T_{e,}$ these are outlined in the following Chapter.

**4.7 REFERENCES**


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# CHAPTER 5. CONCLUSION AND RECOMMENDATIONS

A personal heat strain monitor has the potential to reduce heat illness by monitoring physiological responses to heat stress. Whilst heat stress guidelines are already implemented in many industries, the response of every individual on a daily basis to this heat stress cannot be accurately determined. Awareness of an individuals physiological responses to a heat stress during the exposure would reduce the likelihood of morbidity or mortality from heat illness, as it would allow the individual to make behavioural changes to reduce the physiological strain.

The aim of this project was to develop a theoretical basis upon which a personal heat strain monitor may be developed. Heat strain is evident through changes in several physiological measures: core temperature; heart rate; skin temperature; and sweating. The principal aim of this project was to predict heat strain outside the laboratory through the accurate prediction of oesophageal temperature.

Utilising pre-existing data collected in this laboratory, *post hoc* analyses were performed to predict oesophageal temperature ($T_{es}$) under a range of environmental conditions. The use of an insulated skin temperature ($T_{skin\text{-}insul}$) measurement had been shown to closely track $T_{es}$ (Taylor *et al.* 1998), and this technique formed the basis of the prediction modelling for this project. Four models were developed for each of three air temperature ranges. These prediction equations were then trialed on independent databases to assess their ability to be used on data collected under different conditions. The prediction equations were tested against the actual $T_{es}$ across industrial heat strain safety standards and physiological strain indices.

## 5.1 SUMMARY OF CONCLUSIONS

The following key conclusions may be drawn from the data analysis of the prediction of $T_{es}$ using data previously obtained from within the laboratory:

1. When individual trials were analysed separately, $T_{skin\text{-}insul}$, and $T_{skin\text{-}insul}$ combined with multiple predictor variables were very accurate at predicting $T_{es}$

throughout a trial. Up to 99% of the variance in $T_{es}$ could be explained by the prediction model, and the standard error of the estimate (*S.E.E.*$_y$) values were less than 0.2°C in most analyses. However, as the slope and intercept values within the prediction models varied widely between individuals, development of a generic equation to predict $T_{es}$ was not considered possible from these analyses alone.

2. A more generic equation was developed by combining data collected from different studies within the same air temperature range. These analyses required multiple variables to be used in the prediction models to attain a *S.E.E.*$_y$ of 0.2°C or lower, which was considered the maximal level of error acceptable for use in a heat strain monitor. From these prediction models, it was found that all prediction equations were considered most accurate in the 38-38.5°C $T_{es}$ range. Typically it was observed that under-prediction occurred below these temperatures, and over-prediction above these temperatures. This temperature range is where industrial heat strain guidelines would be most relevant, and is where warnings would be implemented.

3. The application of the prediction models to independent data developed in air temperatures of 30°C and 40°C resulted in the finding that the *S.E.E.*$_y$ values varied between models developed at the same air temperature, and developed for different air temperatures. Additional predictor variables within the prediction models increased the level of error and were above 0.20°C. It was deemed that all equations developed on data collected at 33°C were inappropriate for use in a personal monitoring system as the level of error was two times the recommended value of 0.2°C. Those at an air temperature of 40°C were more accurate, but were still unable to attain the desired standard of 0.2°C or below.

4. The application of the prediction models to the Occupational Health and Safety guidelines, ascertained that the most accurate prediction model was dependant upon whether the actual $T_{es}$ was required, or the change in $T_{es}$. Equations C-33 and C-40 were considered sufficiently accurate at predicting a change in $T_{es}$ of 0.8°C and 1.0°C for use in a personal monitoring system. Use of the

prediction equations to predict the actual $T_{es}$ of 38.0°C and 38.5°C resulted in no equation being considered suitable at a $T_a$ of 33°C, and only Equation A-40 was deemed appropriate for this purpose.

5. The substitution of predicted $T_{es}$, using Equation A-33 and A-40, for the actual $T_{es}$ in the Physiological Strain Index (Moran *et al*, 1998) found that 56% of data was within 0.5 of the actual Physiological Strain Index value at an air temperature of 30°C, and 84.3% at an air temperature of 40°C. This demonstrated that Equation A-40 was more accurate than Equation A-33, and was also considered to attain a level of accuracy considered acceptable for use a in a personal monitor. Based on the results to date, Equation A-40 would be considered suitable for use in a Physiological Strain Index, however it is felt that Equation A-33 may require improvement prior to universal acceptance for use in the Physiological Strain Index. Due to the type of error that was observed in the predicted $T_{es}$, it was identified that the prediction equations were not considered satisfactory for use with the Cumulative Heat Strain Index (Frank *et al*, 2001), as the technique used in this analysis exacerbated these errors.

6. A significant level of variability in the accuracy of predicting $T_{es}$ remains following development of prediction equations. This variability is unexplained, and may result from numerous sources including: thermistor placement, effectiveness of the insulation, and individual factors. Until these can be resolved it would be inappropriate to dismiss the concept of using $T_{skin\text{-}insul}$ to predict $T_{es}$. If further investigation eliminates the technical sources of error, yet the anomalies remain, and the changes that have been observed are due to natural subject variability and changes during the course of a trial, then doubt may be cast over the viability of $T_{skin\text{-}insul}$ as a surrogate measure of $T_{es}$. However, if technical errors are the cause of variability, and these can be eliminated or reduced, then there is a strong case for using $T_{skin\text{-}insul}$ to predict $T_{es}$, particularly if used in conjunction with a heat strain index, such as the PSI.

## 5.2 RECOMMENDATIONS

The findings of this research indicate that there is potential for $T_{skin\text{-}insul}$ to be used as the basis for predicting heat strain. To improve the models that have been developed, and address other concerns. The following recommendations are made:

1. The first priority in continuing to establish the suitability of using insulated skin temperature to predict oesophageal temperature, is to clearly establish a means of identifying any errors in the insulated skin temperature measurement. Errors in the measurement of insulated skin temperature will result in aberrant predictions of heat strain, and will affect the reliability of a personal monitoring system. It is most important to assume that the temperature being measured by the insulated skin temperature probe is in fact that of insulated skin temperature, and not of measurements such as air temperature, which may result if the $T_{skin\text{-}insul}$ thermistor or the insulation lose contact. It is recommended that a technique be developed so that when the thermistor loses contact with the skin, the user and /or the experimenter be made aware that this has occurred, and action taken to correct the loss of contact, and it can be noted in the data.
2. When a suitable technique is developed to identify any erroneous data, the next process to improve the prediction models is to perform a repeated measures study to identify the within-and between-subject variability in insulated skin temperature measurement. It is suggested that if there is low within-subject variability, that the potential reason for this be identified, in order to enable development of a more accurate prediction model.
3. When technical errors are able to be minimised, it would be a worthwhile study to review if there is any time lag between the $T_{skin\text{-}insul}$ and $T_{es}$. The data obtained to date are suggestive that lag may exist, and there is a physiological basis for this since the two measurements are both subject to influence from other factors, and this influence will have an impact on the other measurement, but not immediately due to the physical separation of the measures. Quantifying this lag if it exists, would enable a more accurate model to be developed.

4. The conditions under which the prediction models were developed and tested were controlled laboratory environments, with few external factors for consideration, unlike the research of Eglin and Tipton (2000). When recommendations one and two are implemented, and if a more accurate prediction model is able to be developed it is recommended that the relationship between $T_{es}$ and $T_{skin\text{-}insul}$ be examined under different conditions. Factors that are worthy of further assessment and have practical significance that have not been assessed include: the role of the temperature in the layer between skin and clothing as opposed to $T_a$ alone; effect of predominantly upper body exercise; the effect of radiant heat; and the effect of changing environmental conditions.
5. To expand on the work in recommendation Four above, it is considered critical that through collection of additional data with specific study design, that prediction models be developed for use under resting conditions following exercise and heat exposure, and for use when the workload may be decreasing. In particular it is anticipated that prediction models that utilised $f_c$ as a predictor variable would have the greatest margin for error under these circumstances, as this measure may change more rapidly and these equations will need significant reevaluation. The development of prediction models for these scenarios is important for the ongoing physiological monitoring of workers, and to ensure the safety of workers returning to work.
6. The prediction equations developed at an $T_a$ of 25°C and 27°C in Chapter Three were unable to be validated as there was no independent data collected at those $T_a$. It is considered unlikely that $T_{skin\text{-}insul}$ would be suitable as the sole predictor variable based on the finding that it was a poor predictor of $T_{es}$ under the conditions tested. Therefore it would be unsuitable for use in the Physiological Strain Index and as a predictor of $T_{es}$. However, if data is available to further develop and validate the equations for this air temperature, there may be some practical significance.

## 5.3 REFERENCES

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# APPENDIX A. SIMPLE AND MULTIPLE LINEAR REGRESSION MODELS

**Contents**:

1- Interval Dataset

2- Continuous Dataset

3- Rest and Exercise Dataset

4- Study analysis

5- Database analysis

**Abbreviations /Measurements used:**

| | |
|---|---|
| Adiposity | Relative adiposity |
| Age | Age of subject |
| BMI | Body Mass Index |
| clo | Clothing insulation |
| $f_c$ | Cardiac frequency |
| Height | Height of subject |
| Massnorm | Mass Normalised for height |
| $r^2$ | Proportion of explained variability in $T_{es}$ |
| RPE-C | Rating of perceived exertion- Chest |
| RPE-L | Rating of perceived exertion- Legs |
| RPE-W | Rating of perceived exertion- Whole body |
| SA:Mass | Surface area to mass ratio |
| $S.E.E._y$ | Standard Error of the Estimate |
| Sum6 | Sum 6 Skinfolds |
| Sweatloss | Sweat lost during experimental trial |
| $T_a$ | Air Temperature |
| TD | Thermal Discomfort |
| $T_{es}$ | Oesophageal Temperature |
| TS | Thermal Sensation |
| Tsk | Mean Skin Temperature |
| $T_{skin\text{-}insul}$ | Insulated Skin Temperature |
| $T_{top}$ | Temperature on top of insulation |
| Watts | Workload |

# INTERVAL DATASET

| Subject | Simple Linear regression | $r^2$ | S.E.E.$_y$ | Subject | After multiple linear regression | $r^2$ | S.E.E.$_y$ |
|---|---|---|---|---|---|---|---|
| **Taylor *et al.* (1998) 25ºC** | | | | **Taylor *et al.* (1998) 25ºC** | | | |
| TK1 | $T_{es} = 27.18+0.29*T_{skin-insul}$ | 0.81 | 0.11 | TK1 | $T_{es}=36.4285+0.0091*f_c$ | 0.81 | 0.11 |
| TK2 | $T_{es} = 16.83+0.57*T_{skin-insul}$ | 0.80 | 0.17 | TK2 | $T_{es}=41.6270-0.1745*T_{sk}+0.0162*f_c$ | 0.84 | 0.15 |
| RR | $T_{es} = 14.09+0.65*T_{skin-insul}$ | 0.88 | 0.18 | RR | $T_{es}=35.4991+0.0167*f_c$ | 0.88 | 0.18 |
| RO | $T_{es} = 14.55+0.65*T_{skin-insul}$ | 0.94 | 0.12 | RO | $T_{es}=20.3613+0.0045*Watts+0.4757*T_{skin-insul}$ | 0.96 | 0.11 |
| MP | $T_{es} = 12.03+0.7*T_{skin-insul}$ | 0.90 | 0.15 | MP | $T_{es}=35.6677+0.0153*f_c$ | 0.90 | 0.15 |
| JR | $T_{es} = 9.47+0.77*T_{skin-insul}$ | 0.83 | 0.15 | JR | $T_{es}=41.4446-0.1762*T_{sk}+0.0167*f_c$ | 0.86 | 0.14 |
| AZ | $T_{es} = 19.222+0.5*T_{skin-insul}$ | 0.82 | 0.15 | AZ | $T_{es}=36.1194+0.0123*f_c$ | 0.82 | 0.15 |
| **Wilsmore (1997) 27ºC** | | | | **Wilsmore (1997) 27ºC** | | | |
| SG | $T_{es} = 18.42+0.52*T_{skin-insul}$ | 0.96 | 0.07 | SG | $T_{es}=30.5418+0.1546*T_{sk}+0.0110*f_c$ | 0.98 | 0.04 |
| PS | $T_{es} = 13.83+0.67*T_{skin-insul}$ | 0.94 | 0.09 | PS | $T_{es}=9.4530+0.8306*T_{sk}$ | 0.94 | 0.09 |
| PM | $T_{es} = 28.1+0.26*T_{skin-insul}$ | 0.89 | 0.09 | PM | $T_{es}=19.9265+0.5176*T_{sk}$ | 0.89 | 0.09 |
| NT | $T_{es} = 23.74+0.37*T_{skin-insul}$ | 0.73 | 0.10 | NT | $T_{es}=10.5506-0.0033*Watts+0.7420*T_{skin-insul}$ | 0.87 | 0.07 |
| MP | $T_{es} = 30.99+0.17*T_{skin-insul}$ | 0.79 | 0.09 | MP | $T_{es}=30.9942+0.1716*T_{skin-insul}$ | 0.79 | 0.09 |
| JW | $T_{es} = 18.89+0.53*T_{skin-insul}$ | 0.94 | 0.07 | JW | $T_{es}=18.8932+0.5274*T_{skin-insul}$ | 0.94 | 0.07 |
| JH | $T_{es} = 21.27+0.45*T_{skin-insul}$ | 0.80 | 0.12 | JH | $T_{es}=21.2710+0.4476*T_{skin-insul}$ | 0.80 | 0.12 |
| ES | $T_{es} = 15.68+0.6*T_{skin-insul}$ | 0.90 | 0.11 | ES | $T_{es}=-3.0413-0.0157*f_c+1.1663*T_{skin-insul}$ | 0.96 | 0.08 |
| JC | $T_{es} = 21.71+0.43*T_{skin-insul}$ | 0.85 | 0.10 | JC | $T_{es}=13.3770+0.4033*T_{sk}+0.2797*T_{skin-insul}$ | 0.96 | 0.06 |
| EB | $T_{es} = 23.38+0.38*T_{skin-insul}$ | 0.92 | 0.07 | EB | $T_{es}=23.3812+0.3804*T_{skin-insul}$ | 0.92 | 0.07 |
| DI | $T_{es} = 14.19+0.63*T_{skin-insul}$ | 0.83 | 0.11 | DI | $T_{es}=15.6646+0.6261*T_{sk}$ | 0.83 | 0.11 |
| AW | $T_{es} = 19.88+0.5*T_{skin-insul}$ | 0.72 | 0.15 | AW | $T_{es}= 14.2455+ 0.1131*RPE\text{-}C +0.6646*T_{sk}$ | 0.98 | 0.04 |
| **Taylor *et al.* (1998) 33ºC** | | | | **Taylor *et al.* (1998) 33ºC** | | | |
| | | | | | $T_{es} = 2.3999-0.0017*watts-$ | | |
| TK1 | $T_{es} = 18.52+0.52*T_{skin-insul}$ | 0.73 | 0.26 | TK1 | $0.3561*T_{sk}+0.0122*f_c+1.2489*T_{skin-insul}$ | 0.73 | 0.26 |
| RR25 | $T_{es} = 15.92+0.59*T_{skin-insul}$ | 0.97 | 0.12 | RR25 | $T_{es}=7.0597+0.0645*TD+0.0033*Watts+0.7976*T_{sk}$ | 1.00 | 0.04 |
| RO | $T_{es} = 2.98+0.93*T_{skin-insul}$ | 0.94 | 0.12 | RO | $T_{es}=36.3901-0.0042*f_c+0.1516*RPE\text{-}C$ | 0.97 | 0.10 |
| JR | $T_{es} = -12.61+1.35*T_{skin-insul}$ | 0.95 | 0.13 | JR | $T_{es}=-12.6135+1.3509*T_{skin-insul}$ | 0.95 | 0.13 |
| AZ | $T_{es} = 13.4+0.65*T_{skin-insul}$ | 0.80 | 0.22 | AZ | $T_{es}=13.4030+0.6530*T_{skin-insul}$ | 0.80 | 0.22 |
| TK2 | $T_{es} = -1.21+1.04*T_{skin-insul}$ | 0.90 | 0.19 | TK2 | $T_{es}=9.4215+0.2073*TS+0.7085*T_{skin-insul}$ | 0.94 | 0.15 |
| **Armstrong and Fogarty (1999)** | | | | **Armstrong and Fogarty (1999)** | | | |
| AM | $T_{es} =-11.04+1.31*T_{skin-insul}$ | 0.89 | 0.19 | AM | $T_{es}=34.7776+0.0231*f_c$ | 0.89 | 0.19 |
| AF | $T_{es} = 5.23+0.87*T_{skin-insul}$ | 0.88 | 0.07 | AF | $T_{es}=37.1246+0.0437*RPE\text{-}W$ | 0.88 | 0.07 |
| AZ | $T_{es} = 9.98+0.75*T_{skin-insul}$ | 0.94 | 0.09 | AZ | $T_{es}=7.4021+0.8526*T_{top}$ | 0.97 | 0.09 |
| JB | $T_{es} = 1.40+0.97*T_{skin-insul}$ | 0.85 | 0.11 | JB | $T_{es}=36.1680+0.1091*RPE\text{-}W$ | 0.85 | 0.11 |
| BW | $T_{es} = -18.34+1.51*T_{skin-insul}$ | 0.97 | 0.11 | BW | $T_{es}=-18.3382+1.5086*T_{skin-insul}$ | 0.97 | 0.11 |
| **Taylor *et al.* (1998) 40ºC** | | | | **Taylor *et al.* (1998) 40ºC** | | | |
| TK2 | $T_{es} = -20.69+1.56*T_{skin-insul}$ | 0.92 | 0.17 | TK2 | $T_{es} = 11.4389-0.3252*T_{sk}+0.0122*f_c+0.9714*T_{skin-insul}$ | 0.96 | 0.13 |
| TK1 | $T_{es} = -21.6+1.58*T_{skin-insul}$ | 0.96 | 0.09 | TK1 | $T_{es}=-21.6040+1.5767*T_{skin-insul}$ | 0.96 | 0.09 |
| RO | $T_{es} =-6.83+1.16*T_{skin-insul}$ | 0.97 | 0.09 | RO | $T_{es}=9.2326+0.1210*TD+0.0043*Watts+0.7298*T_{skin-insul}$ | 1.00 | 0.03 |
| MP | $T_{es} =-19.22+1.51*T_{skin-insul}$ | 0.79 | 0.30 | MP | $T_{es}=26.2602+0.5372*T_{skin-insul}*0.2926*T_{sk}+0.1858*RPE\text{-}C$ | 0.99 | 0.08 |
| JR | $T_{es} = -18.83+1.37*T_{skin-insul}$ | 0.85 | 0.20 | JR | $T_{es}=34.7663+0.0220*f_c$ | 0.90 | 0.16 |
| AZ | $T_{es} = -7.4+1.17*T_{skin-insul}$ | 0.99 | 0.05 | AZ | $Tes=-8.8539-0.3441*TD+0.5316*T_{sk}+0.7100*T_{skin-insul}$ | 1.00 | 0.03 |
| **Wilsmore (1997) 40ºC** | | | | **Wilsmore (1997) 40ºC** | | | |
| SG | $T_{es} = 3.72+0.90*T_{skin-insul}$ | 0.94 | 0.12 | SG | $T_{es}=2.6056+0.0071*f_c+0.9334*T_{sk}$ | 0.99 | 0.06 |
| PS | $T_{es} = -2.95+1.09*T_{skin-insul}$ | 0.98 | 0.10 | PS | $T_{es}=6.1318-0.0980*TD+0.1347*RPEL+0.8101*T_{skin-insul}$ | 1.00 | 0.03 |
| PM | $T_{es} = -20.87+1.57*T_{skin-insul}$ | 0.95 | 0.13 | PM | $T_{es}=9.5947+0.7053*T_{skin-insul}+0.0141*f_c$ | 0.98 | 0.08 |
| NT | $T_{es} = -0.95+1.02*T_{skin-insul}$ | 0.98 | 0.07 | NT | $T_{es}=-7.9503-0.070*RPE\text{-}L+1.2354*T_{skin-insul}$ | 0.99 | 0.06 |
| MP | $T_{es} = 9.27+0.75*T_{skin-insul}$ | 0.94 | 0.10 | MP | $T_{es}=15.4010+0.0050*f_c+0.5730*T_{skin-insul}$ | 0.96 | 0.09 |
| JW | $T_{es} = -7.02+1.2*T_{skin-insul}$ | 0.87 | 0.15 | JW | $T_{es}=36.2187+0.4883*TD$ | 0.87 | 0.15 |
| JH | $T_{es} = -1.74+1.05*T_{skin-insul}$ | 0.88 | 0.18 | JH | $T_{es}=-1.7431+1.0514*T_{skin-insul}$ | 0.88 | 0.18 |
| JC | $T_{es} = 32.92+0.13*T_{skin-insul}$ | 0.88 | 0.22 | JC | $T_{es}=21.3150+0.1710*T_{skin-insul}+1.0085*TS$ | 0.93 | 0.18 |
| JB | $T_{es} = -11.83+1.33*T_{skin-insul}$ | 0.98 | 0.08 | JB | $T_{es}=34.7441-0.0046*Watts+0.2706*RPE\text{-}L$ | 1.00 | 0.04 |
| GP | $T_{es} = -5.31+1.15*T_{skin-insul}$ | 1.00 | 0.05 | GP | $T_{es}=-5.3090+101467*T_{skin-insul}$ | 1.00 | 0.05 |
| ES | $T_{es} = -2.25+1.07*T_{skin-insul}$ | 0.97 | 0.10 | ES | $T_{es}=6.0373+0.0322*RPE\text{-}L+0.8414*T_{skin-insul}$ | 0.98 | 0.08 |
| EB | $T_{es} = -5.44+1.15*T_{skin-insul}$ | 0.79 | 0.13 | EB | $T_{es}=-28.9005+0.8361*T_{sk}+0.9559*T_{skin-insul}$ | 0.93 | 0.08 |
| DI | $T_{es} = -13.52+1.36*T_{skin-insul}$ | 0.95 | 0.13 | DI | $T_{es}=35.7484+0.6870*TD$ | 0.95 | 0.13 |
| CC | $T_{es} = 5.0+0.87*T_{skin-insul}$ | 0.96 | 0.16 | CC | $T_{es}=4.9976+0.8693*T_{skin-insul}$ | 0.96 | 0.16 |
| BW | $T_{es} = -10.57+1.29*T_{skin-insul}$ | 0.91 | 0.14 | BW | $T_{es}=13.9517+0.5641*T_{skin-insul}+0.2546*TS$ | 0.95 | 0.11 |
| AW | $T_{es} = -0.06+1.01*T_{skin-insul}$ | 0.97 | 0.05 | AW | $T_{es}=35.9260+0.1643*RPE\text{-}W$ | 0.97 | 0.05 |
| AH | $T_{es} = 22.61+0.39*T_{skin-insul}$ | 0.88 | 0.11 | AH | $T_{es}=34.2868+0.2967*TS$ | 0.88 | 0.11 |

## CONTINUOUS DATASET

| Subject | Simple Linear regression | Subject | After multiple linear regression | $r^2$ | *S.E.E.*$_y$ |
|---|---|---|---|---|---|
| **Taylor *et al.* (1998) 25ºC** | | **Taylor *et al.* (1998) 25oC** | | | |
| TK1 | $T_{es} = 24.8+0.36*T_{Skin-insul}$ | TK1 | $T_{es}=32.9115+0.0011*Watts+0.1081*T_{Skin-insul}+0.0055*f_c$ | 0.79 | 0.14 |
| TK2 | $T_{es} = 18.06+0.54*T_{Skin-insul}$ | TK2 | $T_{es}=19.2028-0.0014*Watts+0.0064*f_c-0.4207*T_{sk}+0.8810*T_{Skin-insul}$ | 0.88 | 0.14 |
| RR | $T_{es} = 18.89 +0.52*T_{Skin-insul}$ | RR | $T_{es}=22.1648+0.0076*f_c+0.4027*T_{Skin-insul}$ | 0.84 | 0.21 |
| RO | $T_{es} = 17.08+0.58*T_{Skin-insul}$ | RO | $T_{es}=21.6219-0.2316*T_{sk}+0.0052*f_c+0.6422*T_{Skin-insul}$ | 0.92 | 0.14 |
| MP | $T_{es} = 12.07+0.7*T_{Skin-insul}$ | MP | $T_{es}=28.2542-0.1026*T_{sk}+0.2933*T_{Skin-insul}-0.0042*Watts+0.0220*f_c$ | 0.90 | 0.16 |
| JR | $T_{es} = 7.46+0.82*T_{Skin-insul}$ | JR | $T_{es}=21.2768-0.1188*T_{sk}-0.0020*Watts+0.5173*T_{Skin-insul}+0.0123*f_c$ | 0.83 | 0.16 |
| AZ | $T_{es} = 24.91+0.34*T_{Skin-insul}$ | AZ | $T_{es}=21.0817-0.0023*Watts-0.3258*T_{sk}+0.7091*T_{Skin-insul}+0.0131*f_c$ | 0.73 | 0.18 |
| **Wilsmore (1997) 27ºC** | | **Wilsmore (1997) 27ºC** | | | |
| SG | $T_{es} = 20.31+0.46*T_{Skin-insul}$ | SG | $T_{es}=29.3917+0.1924*T_{sk}+0.0096*f_c$ | 0.89 | 0.08 |
| PS | $T_{es} = 16.06+0.6*T_{Skin-insul}$ | PS | $T_{es}=12.2124+0.7498*T_{sk}$ | 0.87 | 0.12 |
| PM | $T_{es} = 29.39+0.22*T_{Skin-insul}$ | PM | $T_{es}=24.4527+0.2283*T_{sk}+0.1458*T_{Skin-insul}$ | 0.90 | 0.06 |
| NT | $T_{es} = 22.1+0.41*T_{Skin-insul}$ | NT | $T_{es}=17.8829-0.0011*Watts-0.2817*T_{sk}+0.7929$ | 0.86 | 0.07 |
| MP | $T_{es} = 31.88+0.15*T_{Skin-insul}$ | MP | $T_{es}=25.4783+0.2233*T_{sk}-0.0047*f_c+0.1294*T_{Skin-insul}$ | 0.85 | 0.06 |
| JW | $T_{es} = 21.04+0.47*T_{Skin-insul}$ | JW | $T_{es}=21.3917-0.0784*T_{sk}+0.0049*f_c-0.0022*Watts+0.5171*T_{Skin-insul}$ | 0.94 | 0.06 |
| JH | $T_{es} = 21.91+0.43*T_{Skin-insul}$ | JH | $T_{es}=21.9101+0.4301*T_{Skin-insul}$ | 0.83 | 0.10 |
| ES | $T_{es} = 17.35+0.55*T_{Skin-insul}$ | ES | $T_{es}=15.2182+0.3094*T_{sk}+0.3176*T_{Skin-insul}$ | 0.95 | 0.06 |
| JC | $T_{es} = 23.36+0.38*T_{Skin-insul}$ | JC | $T_{es}=20.9506+0.0037*f_c+0.2329*T_{sk}+0.2203*T_{Skin-insul}$ | 0.94 | 0.06 |
| EB | $T_{es} = 24.27+0.38*T_{Skin-insul}$ | EB | $T_{es}=24.2664+0.3572*T_{Skin-insul}$ | 0.91 | 0.06 |
| DI | $T_{es} = 14.88+0.62*T_{Skin-insul}$ | DI | $T_{es}=35.0284-0.3734*T_{Skin-insul}+0.4397*T_{sk}+0.0025*Watts$ | 0.89 | 0.07 |
| AW | $T_{es} = 19.9+0.5*T_{Skin-insul}$ | AW | $T_{es}=13.1976+0.2187*T_{Skin-insul}+0.4959*T_{sk}$ | 0.86 | 0.09 |
| **Taylor *et al.* (1998) 33ºC** | | **Taylor *et al.* (1998) 33ºC** | | | |
| TK1 | $T_{es} = 7.06+0.82*T_{Skin-insul}$ | TK1 | $T_{es} = 2.3999-0.0017*watts-0.3561*T_{sk}+0.0122*f_c+1.2489*T_{Skin-insul}$ | 0.92 | 0.15 |
| RR | $T_{es} = 16.15+0.58*T_{Skin-insul}$ | RR | $T_{es}=19.4535+0.0060*f_c+0.4870*T_{sk}$ | 0.86 | 0.23 |
| RO | $T_{es} = 6.96+0.82*T_{Skin-insul}$ | RO | $T_{es}=5.8739-0.1255*T_{sk}+0.0029*Watts+0.9693*T_{Skin-insul}$ | 0.88 | 0.15 |
| JR | $T_{es} = -7.91+1.22*T_{Skin-insul}$ | JR | $T_{es}=1.8183+0.0009*Watts-0.1479*T_{sk}+0.0041*f_c+1.0904*T_{Skin-insul}$ | 0.95 | 0.11 |
| AZ | $T_{es} = 11.53+0.7*T_{Skin-insul}$ | AZ | $T_{es}=4.0469-0.3606*T_{sk}+1.2549*T_{Skin-insul}$ | 0.86 | 0.22 |
| TK2 | $T_{es} = 4.52+0.89*T_{Skin-insul}$ | TK2 | $T_{es}=9.1561+0.0012*f_c-0.2539*T_{sk}+0.9980*T_{Skin-insul}$ | 0.94 | 0.13 |
| **Armstrong and Fogarty (1999)** | | **Armstrong and Fogarty (1999)** | | | |
| AM | $T_{es} = -6.63+1.19*T_{Skin-insul}$ | AM | $T_{es}=6.5180+0.0096*f_c-0.1198*T_{top}+0.9134*T_{Skin-insul}$ | 0.96 | 0.11 |
| AF | $T_{es} = -1.87+1.06*T_{Skin-insul}$ | AF | $T_{es}=10.5946+0.0023*f_c+0.0017*Watts-0.0757*T_{top}+0.7814*T_{Skin-insul}$ | 0.89 | 0.09 |
| AZ | $T_{es} = 8.91+0.77*T_{Skin-insul}$ | AZ | $T_{es}=14.1406+0.0007*Watts+0.0073*f_c-0.1851*T_{top}+0.7836*T_{Skin-insul}$ | 0.92 | 0.16 |
| JB | $T_{es} = 0.85+0.11*T_{Skin-insul}$ | JB | $T_{es}=12.9042-0.0007*Watts-0.0247*T_{top}+0.0050*f_c+0.6686*T_{Skin-insul}$ | 0.85 | 0.11 |
| BW | $T_{es} = -9.85+1.28*T_{Skin-insul}$ | BW | $T_{es}=-6.0261-0.0372*T_{top}+0.0074*f_c+1.1785*T_{Skin-insul}$ | 0.96 | 0.12 |
| **Taylor *et al.* (1998) 40ºC** | | **Taylor *et al.* (1998) 40ºC** | | | |
| TK2 | $T_{es} = -8.14+1.22*T_{Skin-insul}$ | TK2 | $T_{es}= -2.5491-0.0012*Watts+0.0078*f_c-0.02894*T_{sk}+1.3306*T_{Skin-insul}$ | 0.92 | 0.17 |
| TK1 | $T_{es} = -6.74+1.18*T_{Skin-insul}$ | TK1 | $T_{es}=0.8376-0.0006*Watts-0.1797*T_{sk}+0.0066*f_c+1.1337*T_{Skin-insul}$ | 0.95 | 0.11 |
| RO | | RO | $T_{es}=7.6492+0.0184*T_{sk}+0.0062*f_c+0.7417*T_{Skin-insul}$ | 0.90 | 0.14 |
| MP | $T_{es} = -8.08+1.22*T_{Skin-insul}$ | MP | $T_{es}=13.1012-0.0041*Watts+0.5980*T_{Skin-insul}+0.0205*f_c$ | 0.98 | 0.11 |
| JR | $T_{es} = -10.85+1.29*T_{Skin-insul}$ | JR | $T_{es}=8.8584-0.0014*Watts+0.0093*f_c-0.5779*T_{sk}+1.3063*T_{Skin-insul}$ | 0.91 | 0.15 |
| AZ | $T_{es} = -4.2+1.09*T_{Skin-insul}$ | AZ | $T_{es}=-1.1854-0.0014*Watts+0.0043*f_c+0.1418*T_{sk}+0.8634*T_{Skin-insul}$ | 0.99 | 0.07 |
| **Wilsmore (1997) 40ºC** | | **Wilsmore (1997) 40ºC** | | | |
| SG | $T_{es} = -0.98+1.03*T_{Skin-insul}$ | SG | $T_{es}=11.3503-0.0027*Watts+0.0134*f_c+0.6797*T_{sk}$ | 0.97 | 0.10 |
| PS | $T_{es} = -1.97+1.7*T_{Skin-insul}$ | PS | $T_{es}=0.6674-0.0007*Watts+0.0030*f_c-0.4742*T_{sk}+1.4493*T_{Skin-insul}$ | 0.99 | 0.09 |
| PM | $T_{es} = 6.6+0.83*T_{Skin-insul}$ | PM | $T_{es}=24.7649-0.1465*T_{sk}+0.4385*T_{Skin-insul}-0.0045*Watts+0.0179*f_c$ | 0.97 | 0.10 |
| NT | $T_{es} = 0.46+0.99*T_{Skin-insul}$ | NT | $T_{es}=-1.8404+0.0013*f_c-0.0010*Watts+0.2887*T_{sk}+0.7688*T_{Skin-insul}$ | 0.99 | 0.03 |
| MP | $T_{es} = 14.82+0.6*T_{Skin-insul}$ | MP | $T_{es}=23.7597-0.1163*T_{sk}+0.4495*T_{Skin-insul}-0.0024*Watts+0.0115*f_c$ | 0.91 | 0.09 |
| JW | $T_{es} = -4.4+113*T_{Skin-insul}$ | JW | $T_{es}=6.9039-0.4747*T_{sk}+0.0099*f_c+1.2407*T_{Skin-insul}$ | 0.92 | 0.11 |
| JH | $T_{es} = 4.43+0.89*T_{Skin-insul}$ | JH | $T_{es}=9.0727-0.0006*Watts+0.2254*T_{Skin-insul}+0.0044*f_c+0.5445*T_{sk}$ | 0.86 | 0.16 |
| JC | $T_{es} = -8.77+1.24*T_{Skin-insul}$ | JC | $T_{es}=-6.8254+0.0009*f_c-0.0010*Watts-0.4180*T_{sk}+1.5949*T_{Skin-insul}$ | 0.98 | 0.08 |
| JB | $T_{es} = -9.24+1.26*T_{Skin-insul}$ | JB | $T_{es}=15.5685+0.1846*T_{sk}+0.3718*T_{Skin-insul}-0.0043*Watts+0.0127*f_c$ | 0.97 | 0.09 |
| GP | $T_{es} = -3.48+1.1*T_{Skin-insul}$ | GP | $T_{es}=1.0642+0.0017*f_c-0.1119*T_{sk}+0.0008*Watts+1.0743*T_{Skin-insul}$ | 0.99 | 0.07 |
| ES | $T_{es} = -2.9+1.09*T_{Skin-insul}$ | ES | $T_{es}=-1.4591+0.0008*Watts+1.0484*T_{Skin-insul}$ | 0.98 | 0.07 |
| EB | $T_{es} = -1.71+1.05*T_{Skin-insul}$ | EB | $T_{es}=0.1576+0.0066*f_c+0.1774*T_{sk}-0.0023*Watts+0.8067*T_{Skin-insul}$ | 0.90 | 0.08 |
| DI | $T_{es} = -9.41+1.25*T_{Skin-insul}$ | DI | $T_{es}=3.1415+0.2316*T_{sk}+0.0073*f_c+0.6704*T_{Skin-insul}$ | 0.96 | 0.10 |
| CC | $T_{es} = 3.18+0.92*T_{Skin-insul}$ | CC | $T_{es}=3.2569-0.2793*T_{sk}+1.1904*T_{Skin-insul}$ | 0.99 | 0.05 |
| BW | $T_{es} = -6.53+1.18*T_{Skin-insul}$ | BW | $T_{es}=6.8895-0.0003*Watts+0.1370*T_{sk}+0.0042*f_c+0.6789*T_{Skin-insul}$ | 0.96 | 0.07 |
| AW | $T_{es} = 1.26+0.98*T_{Skin-insul}$ | AW | $T_{es}=16.2633-0.0260*T_{sk}+0.0058*f_c+0.5808*T_{Skin-insul}$ | 0.91 | 0.07 |
| AH | $T_{es} = 23.25+0.38*_{Tskin-insul}$ | AH | $T_{es}=22.6378-0.0007*Watts+0.0995*T_{Skin-insul}+0.2853*T_{Sk}+0.0068*f_C$ | 0.90 | 0.09 |

## REST DATSET

| Subject | Regression model | $r^2$ | *S.E.E.*$_y$ |
|---|---|---|---|
| **Taylor *et al.* (1998) 25°C** | | | |
| TK1 | $T_{es}=28.4+0.25*T_{skin\text{-}insul}$ | 0.27 | 0.17 |
| TK2 | $T_{es}=9.47+0.77*T_{skin\text{-}insul}$ | 0.65 | 0.26 |
| RR | $T_{es}=19.89+0.49*T_{skin\text{-}insul}$ | 0.52 | 0.33 |
| RO | $T_{es}=23.87+0.38*T_{skin\text{-}insul}$ | 0.60 | 0.24 |
| MP | $T_{es}=-1.60+1.06*T_{skin\text{-}insul}$ | 0.90 | 0.20 |
| JR | $T_{es}=-15.13+1.43*T_{skin\text{-}insul}$ | 0.78 | 0.21 |
| AZ | $T_{es}=22.78+0.40*T_{skin\text{-}insul}$ | 0.49 | 0.27 |
| **Taylor *et al.* (1998) 33°C** | | | |
| TK1 | $T_{es}=10.07+0.73*T_{skin\text{-}insul}$ | 0.71 | 0.31 |
| RR | $T_{es}=-10.83+1.29*T_{skin\text{-}insul}$ | 0.78 | 0.20 |
| RO | $T_{es}=1.07+0.98*T_{skin\text{-}insul}$ | 0.75 | 0.20 |
| JR | $T_{es}=-5.65+1.16*T_{skin\text{-}insul}$ | 0.94 | 0.11 |
| AZ | $T_{es}=-0.54+1.02*T_{skin\text{-}insul}$ | 0.80 | 0.22 |
| TK2 | $T_{es}=10.62+0.72*T_{skin\text{-}insul}$ | 0.87 | 0.22 |
| **Armstrong and Fogarty (1999)** | | | |
| AM | $T_{es}=-6.66+1.19*T_{skin\text{-}insul}$ | 0.82 | 0.26 |
| AF | $T_{es}=-0.23+1.01*T_{skin\text{-}insul}$ | 0.61 | 0.16 |
| AZ | $T_{es}=-12.74+1.34*T_{skin\text{-}insul}$ | 0.93 | 0.14 |
| JB | $T_{es}=0.45+0.99*T_{skin\text{-}insul}$ | 0.81 | 0.14 |
| BW | $T_{es}=-15.84+01.43*T_{skin\text{-}insul}$ | 0.72 | 0.25 |
| **Taylor *et al.* (1998) 40°C** | | | |
| TK2 | $T_{es}=0.91+0.98*T_{skin\text{-}insul}$ | 0.85 | 0.24 |
| TK1 | $T_{es}=-0.91+1.02*T_{skin\text{-}insul}$ | 0.91 | 0.16 |
| RO | $T_{es}=5.99+0.82*T_{skin\text{-}insul}$ | 0.75 | 0.23 |
| MP | $T_{es}=-2.02+1.05*T_{skin\text{-}insul}$ | 0.94 | 0.17 |
| JR | $T_{es}=2.21+0.94*T_{skin\text{-}insul}$ | 0.95 | 0.08 |
| AZ | $T_{es}=-1.85+1.03*T_{skin\text{-}insul}$ | 0.97 | 0.09 |

## EXERCISE DATASET

| Subject | Regression model | $r^2$ | *S.E.E.*$_y$ |
|---|---|---|---|
| **Taylor *et al.* (1998) 25°C** | | | |
| TK1 | $T_{es}=24.7+0.36*T_{skin\text{-}insul}$ | 0.79 | 0.13 |
| TK2 | $T_{es}=16.23+0.59*T_{skin\text{-}insul}$ | 0.75 | 0.19 |
| RR | $T_{es}=13.34+0.67*T_{skin\text{-}insul}$ | 0.87 | 0.19 |
| RO | $T_{es}=23.87+0.38*T_{skin\text{-}insul}$ | 0.95 | 0.12 |
| MP | $T_{es}=12.5+0.69*T_{skin\text{-}insul}$ | 0.91 | 0.14 |
| JR | $T_{es}=-6.55+0.85*T_{skin\text{-}insul}$ | 0.87 | 0.13 |
| AZ | $T_{es}=20.38+0.47*T_{skin\text{-}insul}$ | 0.82 | 0.14 |
| **Taylor *et al.* (1998) 33°C** | | | |
| TK1 | $T_{es}=2.82+0.93*T_{skin\text{-}insul}$ | 0.89 | 0.18 |
| RR | $T_{es}=-17.55+0.54*T_{skin\text{-}insul}$ | 0.89 | 0.19 |
| RO | $T_{es}=3.47+0.92*T_{skin\text{-}insul}$ | 0.87 | 0.16 |
| JR | $T_{es}=-11.32+1.32*T_{skin\text{-}insul}$ | 0.92 | 0.14 |
| AZ | $T_{es}=16.89+0.56*T_{skin\text{-}insul}$ | 0.76 | 0.20 |
| TK2 | $T_{es}=-0.89+1.03*T_{skin\text{-}insul}$ | 0.92 | 0.14 |
| **Armstrong and Fogarty (1999)** | | | |
| AM | $T_{es}=-11.47+1.32*T_{skin\text{-}insul}$ | 0.87 | 0.19 |
| AF | $T_{es}=4.19+0.90*T_{skin\text{-}insul}$ | 0.43 | 0.15 |
| AZ | $T_{es}=7.99+0.80*T_{skin\text{-}insul}$ | 0.97 | 0.09 |
| JB | $T_{es}=6.76+0.83*T_{skin\text{-}insul}$ | 0.83 | 0.10 |
| BW | $T_{es}=-15.06+01.42*T_{skin\text{-}insul}$ | 0.98 | 0.09 |
| **Taylor *et al.* (1998) 40°C** | | | |
| TK2 | $T_{es}=-18.32+1.49*T_{skin\text{-}insul}$ | 0.89 | 0.19 |
| TK1 | $T_{es}=-20.5+1.55*T_{skin\text{-}insul}$ | 0.93 | 0.11 |
| RO | $T_{es}=-3.53+1.07*T_{skin\text{-}insul}$ | 0.94 | 0.10 |
| MP | $T_{es}=-19.96+1.53*T_{skin\text{-}insul}$ | 0.77 | 0.29 |
| JR | $T_{es}=-16.67+1.44*T_{skin\text{-}insul}$ | 0.86 | 0.19 |
| AZ | $T_{es}=--7.23+1.17*T_{skin\text{-}insul}$ | 0.99 | 0.05 |

## STUDY ANALYSIS

| Analysis type | Regression Model | $r^2$ | $S.E.E._y$ |
|---|---|---|---|
| **Analysis One** | $r^2 S.E.E._y$ | | |
| Taylor *et al.* (1998) 25ºC | $T_{es}=20.3095+0.4787*T_{skin\text{-}insul}$ | 0.52 | 0.30 |
| Wilsmore (1997) 27ºC | $T_{es}=29.5734+0.2166*T_{skin\text{-}insul}$ | 0.16 | 0.30 |
| Taylor *et al.* (1998) 33ºC | $T_{es}=10.5503+0.7294*T_{skin\text{-}insul}$ | 0.78 | 0.25 |
| Armstrong and Fogarty (1999) | $T_{es}=2.4574+0.9476*T_{skin\text{-}insul}$ | 0.64 | 0.30 |
| Taylor *et al.* (1998) 40ºC | $T_{es}=9.9008+0.736*T_{skin\text{-}insul}$ | 0.55 | 0.35 |
| Wilsmore (1997) 40ºC | $T_{es}=0.5969+0.9886*T_{skin\text{-}insul}$ | 0.81 | 0.25 |
| **Analysis Two** | | | |
| Taylor *et al.* (1998) 25ºC | $T_{es}=32.0751-0.1578*T_{sk}+0.2566*T_{skin\text{-}insul}+0.121*f_c$ | 0.85 | 0.17 |
| Wilsmore (1997) 27ºC | $T_{es}=38.3504+0.0009*Watts-0.0636*T_{skin\text{-}insul}+0.0111*f_c$ | 0.47 | 0.25 |
| Taylor *et al.* (1998) 33ºC | $T_{es}=22.7840-0.012*Watts-0.1132XT_{sk}+0.4659*T_{skin\text{-}insul}$ | 0.89 | 0.18 |
| Armstrong and Fogarty (1999) | $T_{es}=12.7013-0.0434*T_{sk}+0.0068*f_c+0.6853*T_{skin\text{-}insul}$ | 0.77 | 0.23 |
| Taylor *et al.* (1998) 40ºC | $T_{es}=19.4028+0.0628*T_{sk}+0.0077*f_c+0.0036*Watts+0.3859*T_{skin\text{-}insul}$ | 0.87 | 0.2 |
| Wilsmore (1997) 40ºC | $T_{es}=8.6751+0.0014*Watts+0.1046*T_{sk}+0.0043*f_c+0.6534*T_{skin\text{-}insul}$ | 0.86 | 0.21 |
| **Analysis Three** | | | |
| Taylor *et al.* (1998) 25ºC | $T_{es}=32.5668+0.0316*TD+0.0224*RPE\text{-}C-0.1697*T_{sk}+0.2543*T_{skin\text{-}insul}+0.0098*f_c$ | 0.86 | 0.16 |
| Wilsmore (1997) 27ºC | $T_{es}=34.0142+0.0803*T_{skin\text{-}insul}-0.0764*TD-0.0571*RPE\text{-}C+0.0656*RPE\text{-}W-0.01049*TS+0.0135*f_c$ | 0.67 | 0.2 |
| Taylor *et al.* (1998) 33ºC | $T_{es}=24.1218+0.0405*TD-0.0967*T_{sk}+0.1005*TS-0.0405*RPE\text{-}L+0.3992*T_{skin\text{-}insul}+0.0121*f_c$ | 0.91 | 0.16 |
| Armstrong and Fogarty (1999) | $T_{es}=12.7013-0.0434*T_{sk}+0.0068*f_c+0.6853*T_{skin\text{-}insul}$ | 0.77 | 0.23 |
| Taylor *et al.* (1998) 40ºC | $T_{es}=18.2166+0.0329*RPE\text{-}L+0.0565*T_{sk}+0.0745*TD-0.0653*RPE\text{-}C+0.0073*f_c+0.0042*Watts+0.4278*T_{skin\text{-}insul}$ | 0.88 | 0.19 |
| Wilsmore (1997) 40ºC | $T_{es}=7.8625+0.0769*T_{sk}+0.0650*TD+0.0022*Watts+0.0048*f_c=-.0495*RPE\text{-}C+0.7077*T_{skin\text{-}insul}$ | 0.88 | 0.2 |
| **Analysis Four** | | | |
| Taylor *et al.* (1998) 25ºC | $T_{es}=30.2388-0.0007*Watts+0.0046*height+0.0233*RPE\text{-}C-0.1996*T_{sk}+0.3239*T_{skin\text{-}insul}+0.0107*f_c$ | 0.87 | 0.16 |
| Wilsmore (1997) 27ºC | $T_{es}=39.6186+0.0019*f_c+0.0225*RPE\text{-}L-24.9696*SA{:}Mass+0.1872*TD-0.0232*Massnorm-0.0213*age+0.0471*sum6-0.0534*Adiposity$ | 0.84 | 0.014 |
| Taylor *et al.* (1998) 33ºC | $T_{es}=24.1347-0.1227*sweatloss-0.2017*T_{sk}-0.0016*Sum6+0.5282*T_{skin\text{-}insul}+0.112*f_c$ | 0.92 | 0.15 |
| Armstrong and Fogarty (1999) | $T_{es}=8.2837+0.0023*Watts-0.1095*T_{sk}-0.1571*age+0.0373*Massnorm+0.9260*T_{skin\text{-}insul}$ | 0.9 | 0.15 |
| Taylor *et al.* (1998) 40ºC | $T_{es}=20.8756+0.0059*Sum6+0.1223*TD-0.0119*Adiposity+0.3158*T_{skin\text{-}insul}-0.0374*age+0.0652*Massnorm+0.0132*f_c$ | 0.91 | 0.17 |
| Wilsmore (1997) 40ºC | $T_{es}=15.9341+0.0544*TS-0.0141*mass-144.8847*SA{:}Mass+0.0700*TD-0.1507*Sweatloss-0.0424*RPE\text{-}C-0.0042*Sum6+0.0074*f_c+0.6919*T_{skin\text{-}insul}$ | 0.91 | 0.17 |

# DATABASE ANALYSIS

| Database | | | |
|---|---|---|---|
| **Analysis One** | **Regression Model** | **$r^2$** | ***S.E.E.*$_y$** |
| 1 | $T_{es}=23.311+0.3929*T_{skin-insul}$ | 0.38 | 0.35 |
| 2 | $T_{es}=8.62151+0.7814*T_{skin-insul}$ | 0.72 | 0.25 |
| 3 | $T_{es}=6.0741+0.8407*T_{skin-insul}$ | 0.71 | 0.30 |
| **Analysis Two** | | | |
| 1 | $T_{es}=35.22+0.06*clo-0.02*T_{sk}+0.01*f_c+0.05*T_{skin-insul}$ | 0.72 | 0.25 |
| 2 | $T_{es}=20.1219+0.0099*f_c+0l4361*T_{skin-insul}$ | 0.83 | 0.20 |
| 3 | $T_{es}=12.4999-0.2661*clo+0.0024*Watts+0.1256*T_{sk}+0.0049*f_c+0.5266*T_{skin-insul}$ | 0.85 | 0.20 |
| **Analysis Three** | | | |
| 1 | $T_{es}=34.1254+0.0333*Ta-0.1003*TS+0.0293*RPE\text{-}W+0.0127*f_c+0.0439*T_{skin-insul}$ | 0.78 | 0.2 |
| 2 | $T_{es}=20.1219+0.0099*f_c+0.4361*T_{skin-insul}$ | 0.83 | 0.20 |
| 3 | $T_{es}=12.4399-0.2105*clo+0.0943*TD-0.055*TS+0.0219*RPE\text{-}L-0.0564*RPE\text{-}C+0.0033*Watts$ $+0.0921*T_{sk}$ $+0.0052*f_c+0.574*T_{skin-insul}$ | 0.86 | 0.20 |
| **Analysis Four** | | | |
| 1 | $T_{es}=0.5299*clo-22.8076*SA:Mass-0.0137*age-0.0155*Massnorm-0.0239*Sum6+0.0219*adiposity+$ $0.0208*height+0.0961*TD-0.0637*TS\_0.0301*RPE\text{-}W+0.0073*f_c+0.1044*T_{sk}in=insul$ | 0.85 | 0.20 |
| 2 | $T_{es}=22.3495+0.0326*Sweatloss-0.0144*height+0.0072*RPE\text{-}W+-.0025*Watts+0.0054*f_c+$ $0.4484*T_{skin-insul}$ | 0.86 | 0.20 |
| 3 | $T_{es}=30.4885-0.0721*BMI-472.235*SA:Mass+0.017*Sum6--0.0204*Adiposity-0.0496*Mass+$ $0.0009*Watts+0.13*T_{Sk}+0.0073*f_c+0.5112*T_{skin-insul}$ | 0.75 | 0.20 |

# APPENDIX B. IMPLEMENTATION OF THE THEORETICAL BASIS FOR A PERSONAL HEAT STRAIN MONITOR

The following guidelines have been devised as a recommendation for the potential basis for personal heat strain monitoring based on the current research. As noted above, there is still considered a high degree of error within some of these prediction models, and these must be taken into consideration. It is considered that the prediction models would be used with existing heat strain guidelines providing the basis for the system.

## Predicting heat strain at air temperatures of less than 30°C

It is considered inappropriate to use equations that only use $T_{skin-insul}$ for air temperatures at less than 30°C based on the results obtained in this research. It may be appropriate to use a combination of physical and physiological measures, however this was not able to be validated in the current research, and are therefore not presented.

## Predicting heat strain at air temperatures of 30-36°C

The choice of prediction equation for use in $T_a$ of 30-36°C is dependant upon whether the user is endeavouring to predict the actual oesophageal temperature ($T_{es}$) and use in the Physiological Strain Index (PSI), or to predict the change in $T_{es}$ to use with industrial strain guidelines. Should the requirement be to predict the actual $T_{es}$, Equation A-33 is the most accurate for this purpose. Note must be made that this equation did not attain the desired level of error when validated on independent data.

$$\text{Predicted } T_{es} = -3.5062 * 0.9182 * T_{skin-insul} \qquad \textbf{Equation A-33}$$

Where: $T_{es}$ = Oesophageal temperature (°C)

$T_{skin-insul}$ = Insulated skin temperature (°C)

If the requirement is to predict the change in $T_{es}$, such as for use in occupational health and safety guidelines, then Equation C-33 is recommended for use.

Predicted $T_{es} = 14.262 + 0.5916 * T_{skin\text{-}insul} + 0.0087 * f_c - 0.0023 * \sum 6_{skinfolds} + 0.000 * \text{Mass}$ **Equation C-33**

Where: $T_{es} =$ Oesophageal temperature (°C)

$T_{skin\text{-}insul}$ = Insulated skin temperature (°C)

$f_c =$ heart rate (beats·min)

$\sum 6_{skinfolds}$ = sum of six skinfolds (mm)

Mass = body mass (kg)

To predict the change in $T_{es}$, the predicted $T_{es}$ value from 10-min after the start of exposure to the heat stress, is subtracted from the current time point to indicate the change in predicted $T_{es}$ following 10 min of exposure. The prediction of the PSI value requires use of Equation 2.3 which substitutes Equation A-33 into the PSI equation as the core temperature measurement. Note that the equation to predict $T_{es}$ did not attain th desired level of accuracy, and that if using this equation, this must be considered.

Predicted PSI $= 5(3.5062 * 0.9182 * T_{skin\text{-}insul\ t} - 3.5062 * 0.9182 * T_{skin\text{-}insul\ o}) \cdot (39.5 - 3.5062 * 0.9182 * T_{skin\text{-}insul\ o})^{-1} + 5(f_{ct} - f_{co}) \cdot (180 - f_{c0})^{-1}$ **Equation 2.3 adapted**

*Where*: PSI = Physiological Strain Index

$T_{skin\text{-}insult}$ and $f_{ct}$ = simultaneous measurements of insulated skin temperature ($T_{skin\text{-}insul}$ °C) and heart rate ($f_c$ beats·min$^{-1}$) taken at any time

$T_{skin\text{-}insul0}$ and $f_{c0}$ = Baseline values of $T_{skin\text{-}insul}$ and $f_c$

**Predicting heat strain at air temperatures of 36-40°C**

During an exercise-heat stress at an air temperature of 36-40°C, if the requirement os to predict the actual $T_{es}$, Equation A-40 is the most accurate model. Note must be made that this equation did not attain the desired level of error when validated on independent data, with the $S.E.E_{.y}$ value exceeding 0.2°C.

$$\text{Predicted } T_{es} = 5.4784 * 0.8569 * T_{skin\text{-}insul} \qquad \textbf{Equation A-40}$$

Where: $T_{es}$ = Oesophageal temperature

$T_{skin\text{-}insul}$ = Insulated skin temperature

If the requirement is to predict the change in $T_{es}$, such as for use in Occupational Health and Safety guidelines, then Equation 5.5 is recommended for use.

$$\text{Predicted } T_{es} = 8.933 + 0.7325 * T_{skin\text{-}insul} + 0.0069 * f_c + 0.0083 * \sum 6_{skinfolds} - 0.0029 * \text{Mass} \qquad \textbf{Equation C-40}$$

Where: $T_{es}$ = Oesophageal temperature (°C)

$T_{skin\text{-}insul}$ = Insulated skin temperature (°C)

$f_c$ = heart rate (beats·min)

$\sum 6_{skinfolds}$ = sum of six skinfolds (mm)

Mass = body mass (kg)

To predict the change in $T_{es}$, the predicted $T_{es}$ measurement at 10-min at the start of exposure, is subtracted from the predicted $T_{es}$ at the current time point. The prediction of the PSI value requires use of Equation 5.6 which substitutes Equation 5.1 into the PSI equation as the core temperature measurement.

$$\text{Predicted PSI} = 5\,(5.4784 * 0.8569 * T_{skin\text{-}insul\ t} - 5.4784 * 0.8569 * T_{skin\text{-}insul\ o}) \cdot (39.5 - 5.4784 * 0.8569 * T_{skin\text{-}insul\ o})^{-1} + 5(HR_t - HR_o) \cdot (180 - HR_0)^{-1} \qquad \textbf{Equation 2.3 adapted}$$

*Where*: PSI = Physiological Strain Index

$T_{skin\text{-}insult}$ and $f_{ct}$ = simultaneous measurements of insulated skin temperature ($T_{skin\text{-}insul}$°C) and heart rate ($f_c$ beats·min$^{-1}$) taken at any time

$T_{skin\text{-}insul0}$ and $f_{c0}$ = Baseline values of $T_{skin\text{-}insul}$ and $f_c$

## Functional considerations for a personal heat strain monitor

### Measurement of insulated skin temperature

The $T_{skin\text{-}insul}$ was measured from the right scapula, using a thermistor, insulated by a 0.5 x 3.0 x 3.0 cm piece of closed-cell foam, and a small wad of cotton wool. This was secured to the scapula (adjacent to spine, at the level of T2-T4) with waterproof tape. It is envisaged that a wireless set-up could be produced to improve the practicality of gaining the measurement and improve comfort for the wearer.

### Heart rate measurement

In the current research, the $f_c$ was measured using a Polar Heart Rate monitor, with a transmitter belt worn around the chest. Strapless heart rate monitors are available and it is recommended that to improve comfort for the user, that this style be implemented for personal monitoring.

### Design of a personal monitoring system

It is envisaged that the display and working components of a heat strain monitor could be incorporated into a wristwatch, and provide an easy-to-read indicator of strain, using the direct measurements of predicted $T_{es}$, $f_c$, or physiological strain index. It is not within the scope of this project to identify the mechanical and electrical requirements for this to occur.