HEAT-SHIELD

Integrated inter-sector framework to increase the thermal resilience of European workers in the context of global warming

Deliverable 2.1: Investigation on parameters relevant to vulnerability of workers

Part 1: Individual heat stress responses: An update

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Part 2: Individual Vulnerabilities – translating strain levels between different groups within the population

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Part 3 Individual vulnerability modelling using thermophysiological models.

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Executive Summary

The main purpose of this report is to consider how the vulnerability of the population, and especially the working population, to climate related heat stress is affected by a number of factors related to the individual's characteristics.
This report consists of three parts. Part 1 provides the outcome of a literature review on individual factors that affect vulnerability to heat stress as a consequence of climate change. The factors considered are: fitness, acclimation, age, body size, body fat, surface area to mass ratio, and gender. Also, given the increase in morbidity due to diabetes, the impact of this disease on heat stress response is considered. Part 2 provides normative data on various groupings discussed in part 1 to allow vulnerability models to be expanded to groups beyond the young healthy male, for which such models are usually developed. Part 3 provides examples of how these individual factors can be incorporated in computer simulation models of human thermoregulation. The latter can be used as one of the approaches to vulnerability modelling.

Part1:

Part 1 focuses on identifying physiological factors of importance for individual work tolerance in the context of occupational health and productivity. A review of the literature identified that the following six main factors should be considered when "heat vulnerability" is to be evaluated: Heat acclimation, fitness, age, gender, body mass, body fat content, and the skin surface area to body mass ratio.

Each factor may be considered independently, but there is also considerable interaction of individual factors with the type of work performed (i.e. fixed or relative exercise) and with environmental parameters (i.e. uncompensable or compensable). If everybody is required to have the same work output (the workload is fixed for all), acclimation, fitness, and body mass are the primary indicators of risk of high body temperature and of high cardiovascular strain, with all three factors having an inverse relation with heat strain. The thermoregulatory benefits of improved fitness and acclimation are lost during uncompensable (i.e. where the body is unable to lose all heat it produces) heat stress, but the reduced cardiovascular strain accompanied with these factors will still have a major impact on work performed in that situation. The impact of individual characteristics on the thermoregulatory and cardiovascular responses for different populations is less clear when people all work at a level that is relative to their own work capacity. However, the reduced sweat gland output in females and older people may increase heat strain over a full working day, compared with young adult males in this condition.

The collated evidence provides information of relevance for physiologists, stakeholders, and policy makers. In light of an increasing global surface temperature, the recommendations made in this report may provide the background information needed to evaluate and address productivity losses induced by heat and develop better mitigating measures. Future research should investigate the heat stress response across a full working day for different populations i.e. fit vs unfit, young vs older, male vs female etc., as so far most research is done for much shorter exposure periods.

Part 2:

In part 2, normative data for each of the identified factors were searched and reviewed, and, where data were found, quantitative values are provided. This was the case for gender, age, and fitness. There is solid existing data to quantify how much work capacity and relative cardiovascular strain are affected by these three parameters. In contrast, the interaction of body characteristics (i.e. size, fat %) and acclimation are less developed in terms of normative data here because they can't predict cardiovascular strain directly (see part 3 for further consideration).
The available normative data on work capacity and relative strain based on workload, $\dot{V}O_{2max}$, and heart rate is also provided.

Data is shown in relation to age groups, based on mean/median values for different age groups, but also the population percentile distribution is provided for $\dot{V}O_{2max}$ / workload in relation to age. We consider that vulnerability models for different subgroups: gender, age, fitness, should include these factors

Part 3

In part 3, we present several algorithms capable of simulating the impact of the earlier identified individual factors. These models integrate the factors of importance for heat balance, including consideration of the factors listed in part 1 and 2. The section builds on the following research performed in 2001:

Havenith, G. (2001). Individualized model of human thermoregulation for the simulation of heat stress response. *Journal of Applied Physiology*, 90(5), 1943-1954.

and the text relates to those summarized in 2016:

Fiala, D., & Havenith, G. (2015). Modelling human heat transfer and temperature regulation. In: The Mechanobiology and Mechanophysiology of Military-Related Injuries (pp. 265-302). Springer International Publishing.

While this section presents the state of the art in terms of individualised modelling, when one combines the knowledge of sections 1, 2 and 3, it is evident that further work is needed in the project to build on this existing knowledge and to provide a complete model of importance for evaluating and identifying individual vulnerability.

Part 1. Individual responses to heat stress: Implications for hyperthermia and physical work capacity

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Abstract

Background

Extreme heat events are increasing in frequency, severity, and duration. It is well known that heat stress can have a negative impact on occupational health and productivity, particularly during physical work. However, there are no up-to-date reviews on how vulnerability to heat changes as a function of individual characteristics in relation to the risk of hyperthermia and work capacity loss. The objective of this narrative review is to examine the role of individual characteristics on the human heat stress response, specifically in relation to hyperthermia risk and productivity loss in hot workplaces. Finally, we aim to generate practical guidance for industrial hygienists considering our findings. Factors included in the analysis were body mass, body surface area to mass ratio, body fat, aerobic fitness and training, heat adaptation, ageing, sex, and chronic health conditions.

Findings

We found the relevance of any factor to be dynamic, based on the work-type (fixed pace or relative to fitness level), work intensity (low, moderate, or heavy work), climate type (humidity, clothing vapour resistance), and variable of interest (risk of hyperthermia or likelihood of productivity loss).

Heat adaptation, high aerobic fitness, and having a large body mass are the most protective factors during heat exposure. Primary detrimental factors include low fitness, low body mass, and lack of heat adaptation. Ageing beyond 50 years, being female, and diabetes are less impactful negative factors, since their independent effect is quite small in well matched participants. Skin surface area to mass ratio, body composition, hypertension, and cardiovascular disease are not strong independent predictors of the heat stress response.

Conclusions

Understanding how individual factors impact responses to heat stress is necessary for the prediction of heat wave impacts on occupational health and work capacity. The recommendations provided in this report could be utilised to help curtail hyperthermia risk and productivity losses induced by heat.

Introduction

Climate change is increasing the frequency, intensity, and duration of extreme heat events. Consequently, the prevalence of occupational heat stress is also increasing, which reduces the ability of workers to live healthy and productive lives (Flouris et al., 2018a). Most affected are those who work with sun exposure, in non air-conditioned work spaces, those who perform heavy work, or those who require protective clothing. Sustained, daily elevations in body temperature can increase the risk ofkidney injuries, and is also strongly linked to workplace accident rates (Tawatsupa et al., 2012, 2013). Heat stress also decreases physical work productivity (Wyndham, 1969), since workers must reduce their work output to minimise physiological strain and risk of heat stroke (Miller et al., 2011). The health and productivity implications of workplace heat decreases national economic income (Hübler et al., 2008), an effect exacerbated with climate change (Hsiang et al., 2017).

Although the link between heat stress, health, and performance on the macro level is well established, the biophysical and physiological factors that impact the vulnerability of the *individual worker* is still debated. While past reviews have addressed the impact of some individual characteristics on the heat stress response, an updated synthesis that has practical use is urgently required. Havenith's report (1985) was extensive for the time, but due to lack of available data the discussion on age and body characteristics were limited, and diabetes was not known to be a relevant factor in thermoregulatory control. Cheung et al., (2000) addressed physiological responses to uncompensable heat stress only, which is relevant in many settings (especially with highly protective clothing) but generally less common than compensable environments (each are defined in the 'Clarification of Terms' section). Kenny and Jay (2013) summarised the independent effect of age, sex, and diabetes on the heat stress response as part of a larger review, but their conclusions are drawn mostly from groups matched for all other characteristics apart from that under investigation, rather than the population distribution. They also do not comment on the cardiovascular adjustments to heat stress, which is relevant because workers seem to pace themselves based on their heart rate (HR), a proxy for cardiovascular strain (Miller et al., 2011).

In the present review, we indeed report on individual differences for matched individuals, but also for unmatched groups, which is a better representation of the population distribution. This approach allows for conclusions to be made on a wider scale, facilitating the development of practical advice for policymakers and industrial hygienists. We also recognise the contribution of large, individual lab studies which use heterogeneous groups and multiple regression to document the most relevant factors governing the heat stress response (Flouris et al., 2018b; Havenith et al., 1995b, 1998; Havenith and van Middendorp, 1990; Notley et al., 2019b). These works are addressed throughout this paper, based on their contribution to understanding the influence of each individual factor described below. However, no one single study can answer all the relevant questions needed to determine the importance of any given individual characteristic. The relative importance of each factor changes based on the environment (hot dry or hot humid), work intensity (low, moderate, or high metabolic rate, Table 1), and work type (fixed or self-paced). Equally important to consider is the cardiovascular response to heat (particularly HR), since this can govern perceived work intensity and thus, work output (discussed in the 'Physiological and Biophysical Aspects of Heat Transfer' section) (Miller et al., 2011). Any impact a single factor has on work capacity therefore has implications for economic production.

The aim of this review is to synthesise the relative importance of individual factors, based on how they can predict the human heat stress response. We base our conclusions on how each factor may be protective against hyperthermia (rises in core temperature) and losses in physical work output during fixed and self-paced work scenarios.

Table 1. Classification of work intensity according to heat production and type of activity.

Class	Average metabolic rate (with range in brackets)		Examples
	W/m^{-2}	W	
Resting	65 (55 to 70)	115 (100 to 125)	Resting, sitting at ease.
Low metabolic rate	100 (70 to 130)	180 (125 to 235)	Light manual work (writing, typing, drawing, sewing, book-keeping); hand and arm work (small bench tools, inspection, assembly or sorting or light materials); arm and leg work (driving vehicle in normal conditions, operating foot switch or pedal); standing drilling (small parts); milling machine (small parts); coil winding; small armature winding; machining with low power tools; walking up to 2.5 km/h.
Moderate metabolic rate	165 (130 to 200)	295 (235 to 360)	Sustained hand and arm work (hammering in nails, filing); arm and leg work (off-road operation of lorries, tractors or construction equipment); arm and trunk work (work with pneumatic hammer, tractor assembly, plastering, intermittent handling of moderately heavy material, weeding, hoeing, picking fruits or vegetables, pushing or pulling lightweight carts, wheelbarrows, walking at a speed of 2.5 km/h to 5.5 km/h).
High metabolic rate	230 (200 to 260)	415 (360 to 465)	Intense arm and trunk work; carrying heavy material; shovelling; sledgehammer work; sawing; planning or chiselling hard wood; hand mowing; digging; walking at a speed of 5.5 km/h to 7 km/h. Pushing or pulling heavily loaded hand carts or wheelbarrows; chipping castings; concrete block laying.
Very high metabolic rate	290 (>260)	520 (>465)	Very intense activity at fast to maximum pace; working with an axe; intense shovelling or digging; climbing stairs, ramp or ladder; walking quickly with small steps; running; walking at a speed greater than 7 km/h.

Source: International Standards Committee (ISO 8996, 2004).

Methodology

We chose to perform a narrative review due to i) concerns that the systematic review process will omit many studies based on strict inclusion/exclusion criteria, and ii) the broad scope of the present review, which is unsuitable if using the systematic process (Misra and Agarwal, 2018). Articles were obtained by searching relevant keywords into Google Scholar and PubMed databases. The reference list of relevant articles was also scanned for their potential inclusion.

Clarification of terms

This section will aim to improve the translation of findings from laboratory studies to real-world working scenarios. To achieve this aim, we present a clarification of terms used throughout this review.

Core temperature

The term *core temperature* (T_c) is used to reflect the global internal temperature of the body. The rectal (typically 10-12 cm beyond the anal sphincter) and/or oesophaeal (typically level with the left atrium) temperatures are the most adopted tissues used to estimate T_c. Alternative measurements are intestinal temperature, arterial blood, tympanic, and brain temperature, but each have issues of either cost, invasiveness, logistics during exercise, or accuracy, decreasing their use. A further consideration is that there may be a time lag of 10-30 minutes for T_c to reflect whole body heat content (Kenny and Jay, 2013).

Direct calorimetry

Various thermoreceptors sense temperature variations throughout the body to generate an appropriate effector response (Romanovsky, 2018), with the global internal temperature best represented whole body heat content (Kenny and Jay, 2013). Whole-body heat content can be measured with a *direct calorimeter*, a unique tool which generates data on each heat transfer pathway (evaporative, dry, and respiratory), and in combination with indirect calorimetry to measure metabolic rate, whole body heat storage. Using direct calorimetry, differences in whole body heat storage help to identify inter-individual differences in heat exchange pathways (Carter et al., 2014; Flouris et al., 2018b; Kenny et al., 2015; Larose et al., 2013; Notley et al., 2019b; Poirier et al., 2015; Stapleton et al., 2013, 2015). Due to reasons previously described, the device is primarily limited to cycling exercise in hot dry environments, and with high air flow (to minimise sweat drippage) (Cramer and Jay, 2019). Hence, the environment is considered in each study when drawing conclusions about the data from direct calorimetry.

Fixed work rate

Protocols that require participants to work at a *fixed metabolic rate* simulate a constant work rate, not allowing for self-pacing of exercise intensity (Havenith et al., 1998). This type of activity may reflect work on an assembly line where the work pace is fixed for all. The approach is often used in regression studies to determine what individual factors best predict the heat stress response (Cramer and Jay, 2015; Havenith et al., 1995b, 1998; Havenith and van Middendorp, 1990).

Activity at a relative intensity

The term *relative exercise intensity* means the workload is prescribed based on the individual participant's maximal work capacity (Havenith et al., 1998; Periard et al., 2012). Here, fitter people will work at a greater metabolic rate than unfit people to achieve equivalent percentage maximum oxygen uptake ($\dot{V}O_{2max}$). It stands to reason therefore, that results from studies that use a relative intensity can be used to reflect scenarios where physical work is self-paced. This is supported by evidence of self-pacing during actual physical work in the heat (Bröde et al., 2017; Kalkowsky and Kampmann, 2006; Miller et al., 2011; Morrison et al., 1969; Wyndham et al., 1965). In a laboratory setting, the intensity is normally set as a percentage of $\dot{V}O_{2max}$, normally prescribed relative to body mass (ml $O_2 \cdot kg^{-1} \cdot min^{-1}$).

Compensable and uncompensable heat stress

Environments in the present review are often characterised based on whether they are *compensable* or *uncompensable*. A distinction between compensable and uncompensable heat stress is required since it can have implications for the relevance of individual characteristics. These terms describe if metabolic heat production can be matched by heat loss. In compensable heat stress, enough heat can be lost to the environment so that the body is not in a continuous state of heat gain. In hot working scenarios, compensable heat stress is typically associated with work in an environment with low ambient humidity. With uncompensable heat stress, heat production exceeds heat loss potential in that climate, and the body is in a state of continuous heat gain. Thermal compensability can be determined by estimating required evaporative heat loss (E_{req}) and the maximum evaporative capacity of the environment (E_{max}), determined by the humidity, wind speed, and clothing. A work situation is generally considered compensable if $E_{max} > E_{req}$, indicating the environment can accommodate E_{req} for thermal balance.

Relating heart rate to physical work capacity

Physical work capacity defines the ability of an individual to perform maximal physical work. To support skin blood flow requirements during work, cardiac output (primarily mediated by HR) increases as a function of the heat stress severity (Rowell, 1974). Because the WHO have classified occupational work intensities based on HR (Table 2) (Andersen, 1978), HR is considered an integral part of the heat stress response. Moreover, there are a number of large scale field observations showing that workers will pace themselves according to the environmental heat, resulting in a relatively stable working HR regardless of the environmental severity (Kalkowsky and Kampmann, 2006; Miller et al., 2011; Morrison et al., 1969; Vogt et al., 1983; Wyndham, 1973). Since self-pacing is primarily driven by HR (Borg, 1982), those with a more stable and lower HR increase during hot work will likely maintain greater physical work capacity (Jay et al., 2019).

The relative contribution of skin blood flow (SkBF) to heat loss

Control of human core temperature relies on delivery of warm blood from the core to the skin surface. Heat loss from the skin surface to the environment can then occur through dry and/or evaporative pathways. Throughout this review, reference is made to adjustments in SkBF with specific factors, but its contribution to overall heat loss should be nuanced relative to the environment. In resting, normothermic conditions, blood is delivered to the skin at a rate of ~250 ml/min, warming the skin. Heat from the skin surface is then *lost* to the environment (dry heat loss) at a rate similar to metabolic heat *production*, producing heat balance (Charkoudian, 2003). The rate of dry heat loss is therefore modified by SkBF in resting conditions in a cool environment, where it is the primary contributor to overall heat loss. The contribution of dry heat loss (and thus SkBF) to overall heat loss is minimal in hotter conditions due to a narrowing of the skin and air temperature gradient. For instance, at 30°C air temperature, attenuated SkBF causes a faster increase in T_c during activity in the heat, despite similar sweat rates (Balmain et al., 2018). However, at 35°C air temperature, a reduced SkBF in older participants *did not* increase T_c, because dry heat loss was similar in the young and older participants (Havenith et al., 1995b).

Thus, if an individual factor is shown to modify SkBF, this in-of-itself is likely to improve heat loss mainly in conditions permitting high rates of *dry* heat transfer. Such conditions are air temperatures < 30°C, minimal clothing insulation, and high wind speed. All these factors increase rates of dry heat loss from the skin to the environment, rendering an elevation in SkBF beneficial to the heat loss response. A secondary effect of SkBF raising skin temperature is its effect on the saturated vapour pressure on the skin, which increases to a small amount with each degree of increase in skin temperature (Parsons, 2010). This effect increases the vapour pressure gradient from the skin to the environment, increasing sweating efficiency i.e. the proportion off sweat that evaporates, rather than drips from the body (Candas et al., 1979).

The relative contribution of SkBF to work capacity

Important to note is the role of SkBF in overall cardiovascular strain, which impacts work tolerance time in the heat. In several studies throughout this review, differences in *absolute* SkBF do not result in different body temperatures, an observation supported and explained by Kenney and Havenith (1993). However, while changes in *absolute* SkBF may not result in a different T_c (and risk of hyperthermia *per-se*), such differences can have implications for work capacity, depending on the %HRmax required to achieve that SkBF (Rowell, 1974; Rowell et al., 1970). For individual factors that reduce maximum cardiac output (i.e. low fitness, age), a similar, or even lower *absolute* level of SkBF can still represent a greater *relative* cardiovascular strain (in terms of %HR max), which is a major limitation to work capacity in the heat (Cheung and McLellan, 1998; Drinkwater and Horvath, 1979). For example, when comparing young vs older participants, despite *absolute* SkBF being lower in older participants and no corresponding change in T_c (Havenith et al., 1995b), older people required a similar %HRmax to achieve their SkBF, placing similar *relative* stress on the cardiac system to meet the combined oxygen demand of locomotion (active muscle tissues) and thermoregulation (skin tissues). The net result would be a similar "cardiovascular strain" despite reduced SkBF requirements.

The role of clothing on the impact of individual factors

Clothing is a pre-requisite of most occupations but varies depending on the level of protection required. Clothing impacts dry and evaporative heat transfer pathways (Havenith et al., 1999; Holmér et al., 1999), such that the potential for heat loss decreases as a function of the total insulation and evaporative resistance of a given ensemble (Potter et al., 2015). Many of the factors discussed in this review impact heat stress vulnerability through adaptation or maladaptation of the sweating response, which impacts the rate of sweat evaporative heat loss. However, with heavy protective clothing (i.e. NBC protective clothing), sweat evaporation is severely diminished, resulting in similar *thermoregulatory* responses between people of different phenotypes/individual characteristics (Cheung and McLellan, 1998). Clearly, heavy protective clothing that creates an *uncompensable* environment changes the relevance of individual characteristics, compared with environments where sweat output impacts heat loss. We differentiate between compensable and uncompensable heat stress throughout this review, but the reader is also directed to an earlier review which focuses on individual factors during uncompensable heat stress exclusively (Cheung et al., 2000).

Data is limited regarding the impact of typical clothing (i.e. for non-specialist situations) on the relevance of individual factors. However, in the present review, the impact of added clothing will be like that of increasing ambient humidity since both *decrease* compensability in a similar way. Studies that create a more uncompensable environment by increasing humidity (i.e. Havenith et al., 1995a) are therefore likely to serve as a proxy for increasing clothing insulation. This relationship is not perfect however, and more studies are required to investigate the importance of individual characteristics in typical, non-specialist work ensembles.

Determining the hierarchy of individual factors

At the end of each section, we use specific terminology to state the overall impact of an individual factor. We also use that terminology to determine the relative importance of an individual factor as shown in Figure 1. If a factor has a "strong" impact on the heat stress response, it is consistently relevant independent of climate type or workload. If a factor has a "moderate" impact on the heat stress response, its relevance is dependent on climate type or workload. If a factor has a "low" impact on the heat stress response, it has minimal *independent* effect on heat stress vulnerability. With that being said, some factors of "low" impact will be secondary to other factors of strong impact, so may still be important screening tools for individual workers.

Table 2. Relative work intensity classification based on heart rate in young adult males.

Work intensity	**$\dot{V}O_2$ (L·min^{-1})**	**% of $\dot{V}O_2$ max**	**Heart rate (b·min^{-1})**
Light	< 1.0	< 25	<100
Moderate	1.0 – 1.4	26 – 50	100-124
Heavy	1.5 – 2.0	51 – 75	124-150
Very heavy	> 2.0	> 75	>150

Source: (Andersen, 1978)

Morphological differences

Morphological factors have been described as key modulators of individual heat stress responses (Havenith et al., 1998; Havenith, 2001a). Factors included for discussion are body mass, the body surface area to mass ratio (A_D:mass), and body fat.

Body mass

Bergmann's rule suggests that typically, species originating from colder climates will have a larger body mass than those originating from warm, tropical climates (Bergmann, 1847). The rule tends to apply to modern human beings, but only when extreme differences in climate are apparent (i.e. 50º of latitude and/or more than 30º C difference in air temperature) (Foster and Collard, 2013). Here we show that Bergmann's rule does not apply to humans, in that heavier people *are not* more vulnerable to heat compared with smaller people. Bergmann's rule may still apply to extreme geographical changes because i) absolute fluid requirements are lower in smaller people, and ii) being heavier increases metabolic heat production if the activity has a considerable weight bearing component i.e. climbing, jogging etc (Dennis and Noakes, 1999; Marino et al., 2000; Smoljanić et al., 2014). In most occupations, there is minimal weight bearing component and water is not typically in short supply. Below, we discuss the effects of body mass with the assumption that an individual is within a healthy range of body fat.

Fixed work rate

In humans, specific heat capacity defines the amount of energy required to heat the body by 1ºC. The specific heat of most tissue in the body is ~3.65 $kJ \cdot kg^{-1}$, apart from adipose tissue which is ~2.51 $J \cdot g^{-1}$ (Lipkin and Hardy, 1954). Compared with light people, larger people are at an advantage if they work at the same absolute metabolic rate, since their larger heat sink results in more energy being required to raise T_c (Havenith, 1997). Consequently, total body mass below 50 kg has been highlighted as a major risk factor for hot work in general (Wyndham and Heyns, 1973). Body mass has been shown to explain a large portion of the heat stress responses during fixed and relative exercise intensities (Coso et al., 2011; Cramer and Jay, 2014, 2015; Havenith, 1985; Havenith et al., 1995b, 1995a, 1998). Since a larger body mass allows for greater distribution of internal heat (i.e. 'heat sink'), ΔT_c is negatively correlated with body mass during hot work (Coso et al., 2011; Cramer and Jay, 2015; Gagnon et al., 2009, 2013b; Havenith et al., 1995b, 1998; Havenith, 2001a; Lind, 1963). During cycling at a fixed work rate, body mass explained ~40% of ΔT_c, where it is negatively correlated i.e. protective (Cramer and Jay, 2014; Havenith et al., 1998). HR was also negatively correlated with body mass during fixed pace work in both dry and humid conditions (Havenith et al., 1995a), indicating a protective impact on physical work capacity. In occupational settings where the workload is externally governed, it can be assumed that heavier people are less vulnerable to heat stress compared with lighter people. However, upon recovery from heat stress, people with a heavy body mass will generally have a slower rate of T_c decrease compared with smaller people (White et al., 1992). This is relevant for occupations that adopt fixed work/rest cycles because heavier people may take longer to recover to their baseline T_c.

Relative work rate

The effect of total body mass was determined in hot-dry and warm-humid environments during exercise at a relative workload (Havenith et al., 1998). During exercise in a compensable environment, body mass explained ~10% of the ΔT_c, where there was a negative association. In the more uncompensable environment, body mass explained 30% of the ΔT_c, also with a negative association. However, body mass had no independent effect on HR during relative work in dry or humid heat (Havenith et al., 1995a). Therefore, body mass remains protective against hyperthermia at relative workloads, without a strong impact on HR.

In summary, total body mass has a strong impact on the heat stress response in humans, where it is protective against hyperthermia and increased HR during fixed paced work (Havenith et al., 1998). A high body mass remains protective against hyperthermia during self-paced work, without impacting

HR (Havenith et al., 1995a). The findings are unlikely to apply to activities with a heavy weight bearing component.

Surface area to mass ratio

Allen's rule (Allen, 1907) suggests that homoeothermic animals adapted to their thermal environment through evolutionary alterations in the skin surface area to body mass ratio (A_D:mass). In short, the rule suggests that a high A_D:mass decreases heat gain, due to a a larger ratio of cooled tissue (from dry and evaporative heat exchange at the skin) to metabolically active tissue (the body mass reflects this component). Geographical adaptations to heat are evident since humans born in hot climates generally show greater limb length compared with those descending from cold climates (Katzmarzyk and Leonard, 1998; Weinstein, 2005), .

The literature examining the human heat stress response *does not* support Allen's rule. Heavier people mostly have a lower A_D:mass than lighter people, because mass and A_D do not increase in direct proportion to one another. Hence, the proportion of A_D in relation to mass typically decreases as mass increases, unless an individual is exceptionally tall and lean. For example, if an individual was 60 kg and 1.8 m (5.9 ft) tall, their A_D:mass would be 294 $cm^2 \cdot kg^{-1}$. For a heavier person (80 kg) to achieve the same A_D:mass, they would need to be 2.2 m (7.2 ft) tall, clearly not a population norm. Ultimately, there is strong collinearity between mass and A_D:mass in most population samples, meaning that A_D:mass is effectively, another representation of mass itself (Havenith, 2001a; White et al., 1992).

During non-weight bearing activity in the heat, ΔT_c is more related to total body mass compared with A_D:mass. Havenith (2001a) reports total mass to be the most relevant characteristics for heating rates during hot work at a fixed metabolic rate, where A_D:mass was not a stronger predictor. Moreover, A_D:mass generally *increases* as body mass *decreases*, such that a higher A_D:mass is associated with a faster ΔT_c. It was shown in the last section that a lower body mass decreases heat-sink, which results in an increased ΔT_c for lighter people. Hence, during physical work, participants with a higher A_D:mass (smaller people) showed elevated T_c's compared with the heavier people (Cramer and Jay, 2015; Havenith et al., 1998; Havenith, 2001a). Taken together, these findings contradict Allen's and Bergmann's rules. An earlier study analysed sex differences in responses to heat stress, reporting a lower heat gain in females due to their higher A_D:mass (Shapiro et al., 1980). However, the interpretation was shown to be erroneous because the heavier males (i.e. lower A_D:mass) were working at higher rates of heat production than the lighter females (Havenith, 2001a). In humans, A_D:mass only seems relevant for two individuals of the same mass, where increased limb length alters heat exchange with the environment. In environments where air temperature is below skin temperature, having a larger A_D for the same mass *increases* heat loss by convection and radiation. Conversely, when air temperature exceeds skin temperature, more heat will be gained from these dry heat exchange pathways with increasing A_D. An increased A_D will also increase E_{max}, which is beneficial in all heat stress conditions, if sweat can evaporate freely i.e. compensable. It is worth noting that occupational heat stress typically involves short, non-steady state heat stress exposures (Vogt et al., 1983), often not allowing time for steady state sweating to occur. In those scenarios where the skin is not wet, dry heat exchange, primarily determined by the gradient between skin and ambient temperature, will become highly relevant. Overall, body mass is the more relevant characteristic during heat stress.

Similar to the last section, total body mass was a stronger predictor of ΔT_c during recovery compared with A_D:mass (White et al., 1992). However, that study used cold water immersion during recovery, which is applicable for heat stroke recovery but less commonly adopted in occupational settings. More data on the association between body characteristics during recovery from heat stress in cool and hot air is required as it is more applicable to industry.

Overall, A_D:mass *is not* a strong independent predictor of the heat stress response in humans.

Body fat

Based on the physical properties of fat tissue (described below), the WHO suggest that being overweight increases vulnerability to hyperthermia during heat stress (Koppe et al., 2004). Body fat can affect the heat stress response in several ways. Firstly, fat tissue has different heat transfer properties compared with muscle (McIntosh and Anderson, 2010). The comparison between these

tissues is appropriate in the context of comparing individuals with different body compositions. The properties are shown in Table 3.

Table 3. Physical properties of fat and skeletal muscle

	Specific heat capacity, *c*	**Conductivity, *k***	**Density, *p***	**Thermal diffusivity, *a***
	$J \cdot kg^{-1} \cdot °C^{-1}$	$W \cdot m^{-1} \cdot °C$	$kg \cdot m^{3}$	$m^{2} \cdot s^{-1}$
Fat	2065	0.21	909	1.12E-07
Skeletal muscle	3322	0.49	1103	1.34E-07

Source: McIntosh and Anderson (2010).

The specific heat capacity (*c*) of a tissue defines the thermal energy required to raise its temperature by 1°C. Fat has a lower value of *c*, which means it requires less thermal energy to raise its temperature. Fat also has a lower value of *k*, which means less heat propagates from the tissue into the blood stream. These aspects intuitively lead to the assumption that body fat independently changes an individual's vulnerability to heat stress. Importantly however, these values are provided for resting conditions only, not taking into account the fact that during activity, the metabolic heat production of active skeletal muscle will far exceed fat, contributing heavily to whole body heat storage rates (Jay et al., 2007; Kenny and Jay, 2013). However, body fat also increases passive mass carried, another form of load carriage, which elevates metabolic heat production for a given task (Pandolf et al., 1977). Finally, obese humans typically have greater levels of systemic inflammation (Fontana et al., 2007), which, *theoretically*, may predispose this group to heat stroke (Chin et al., 2006). The above factors intuitively lead to the assumption that body fat independently increases vulnerability to heat stress (Havenith, 1997).

A primary supporting article for this assumption showed that overweight army trainees were 70% more likely to develop heat illness in basic training compared with those who have a healthy body fat (Bedno et al., 2010). However, the increased risk of heat illness could have been be due to reduced fitness levels in the overweight recruits (Mondal and Mishra, 2017), which was not accounted for in that study. The extra passive mass carried during the weight bearing activity could have also increased metabolic heat production, contributing to the risk of heat exhaustion. In lab studies which do control for these variables, researchers generally cannot isolate an independent effect of body fat on the heat stress response (Adams et al., 2015; Havenith et al., 1998; Haymes et al., 1974; Jay et al., 2011). Work using a multiple regression approach could not identify body fat as a significant predictor for the heat stress response in dry or humid heat conditions, and at either a fixed or relative exercise intensity (Havenith et al., 1998). Similar findings have been documented in studies using independent matched groups designsin hot (Adams et al., 2015) or warm conditions (Jay et al., 2011). Mechanistically, the potentially insulating effect of fat seems to be outweighed by unimpeded blood flow to the skin surface across the fat layer i.e. blood flow provides a convective short-cut for heat-transport through the fat tissue (Havenith, 2001b). We acknowledge evidence of reduced SkBF in obese vs lean individuals exercising in the heat (Vroman et al., 1983), but given that sweating is not impaired in obese individuals, any influence of fat on SkBF is unlikely to pose significant increases in risk of heat illness (Dervis et al., 2016). On the population level (i.e. not fitness matched), obese individuals are expected to show an increased HR of 20-30 $b \cdot min^{-1}$ during work in hot conditions compared with those of normal body fat (Bar-Or et al., 1969; Haymes et al., 1975).

During exercise in cool conditions, the insulative effect of body fat can increase heat storage rates. At a relative intensity, body fat independently explained 26% of the T_c response in cold conditions, but not in hot conditions (Havenith et al., 1998). Another study found that large differences in body fat of ~21% increased heat gain during fixed intensity exercise in warm conditions (Dervis et al., 2016). Therefore, it appears that the difference in heat storage between high and low-fat populations

increases as the temperature decreases, because the insulative effect of fat takes precedence in colder conditions. Although less specific, the body mass index (BMI) may be a practical guideline when formulating employment standards for hot work. Work using receiver operator characteristic (ROC) curve analysis suggest an upper threshold for BMI of 26 kg·m^2 for protection against heat illness (Flouris et al., 2018b). Since being underweight is also problematic for heat storage capacity, we advise a lower limit of 18.5 kg·m^2, following WHO guidelines.

Overall, body fat *is not* a strong independent predictor of the heat stress response, but in cool conditions, will likely cause faster elevations in T_c at heavy workloads. On a population level, obese individuals are likely to experience a higher HR and produce less physical work during heat stress.

Summary

In the normal range of body fat, total body mass can be a strong predictor of the heat stress response, where it is protective during hot work. The beneficial effect of a high mass is greater during uncompensable heat stress compared with compensable heat stress. The A_D:mass is not a strong predictor of the heat stress response, and is superseded by body mass. On a population level, individuals with high adiposity do not typically show a different ΔT_c than leaner males in hot conditions but may have increased HR's due to (on average) lower fitness levels and more passive mass carried. The independent effect of body fat on thermophysiological responses to exercise are displayed in Table 4.

Practical advice

- If employment standards for hot work are utilised based on body type, they should be based on body mass, and not skin surface area to mass ratio. Heavier people with a normal body fat are at less risk of hyperthermia if the workload is fixed.
- Previous research suggests those under 50 kg should not perform physical work in the heat.
- For general purposes, the body mass index (BMI) should be within 18.5 and 26 kg·m^2.

Table 4. Overview of data relating to the effect of body fat on the heat stress response.

Source	n	Fitness matched?	Condition	Work-type	Absolute difference in body fat %	Sweat threshold (°C)	Sweat rate	Baseline Core temperature (°C)	Peak Core temperature (°C)	Cardiovascular strain
(Bar-Or et al., 1969)	9	No	37°C/15%	Walking on a level treadmill 4.8 km/h	15%	-	↑ 60%	NS	↑ 0.40°C	↑ 20 b/min
(Haymes et al., 1975)	12 (children)	No	48°C/20%	Walking on a level treadmill 4.8 km/h	15%	-	NS	NS	↑ 0.40°C	↑ 30 b/min
(Vroman et al., 1983)	10	Yes	38°C/17%	Cycling at 50% $\dot{V}O_{2max}$ (ml/fat free mass in kg^{-1}/ min^{-1}).	16%	-	-	NS	NS	
(Dervis et al., 2016)	16	Yes	28°C/26%	Cycling at a heat production of 550 W	21%	-	NS	NS	↑ 0.20°C	-
				Cycling at a heat production of 7.5 W/kg lean body mass		-	↓ 34%	NS	↓ 28%	-
(Adams et al., 2015)	20	No	40°C/30%	Cycling a heat production of 300 W	16%	-	NS	NS	NS	NS
				Cycling at a heat production of 175 W/m^{-2}		-	NS	NS	NS	NS
(Limbaugh et al., 2013)	17	Yes	30°C/40%	Cycling at 66 W external work	13%	NS	NS	NS	NS	NS

HR; Heart rate; b/min, heart beats per minute; n, number of subjects; $\dot{V}O_{2max}$, maximal oxygen consumption; W/m^{-2}, Watts per metres squared; NS, not statistically significant; ↑, increased; ↓ decreased; -, not reported.

Aerobic fitness and training

Exercise training evokes a plethora of adaptations relevant to thermoregulation, such as increased cardiac function, plasma volume, and microvascular function (Hellsten and Nyberg, 2016). It is logical to assume, therefore, that the physiological adaptations to endurance training directly improve thermoregulatory and cardiovascular performance during heat stress. In exercise physiology, $\dot{V}O_{2max}$ is the most used index of aerobic fitness. It is most commonly measured through analysis of expired air during maximal aerobic exercise, but can be predicted during cycling or treadmill exercise based on the power output, and speed and grade, respectively (ACSM, 2013; Ludlow and Weyand, 2017). In line with exercise physiology literature, we use $\dot{V}O_{2max}$ to categorise aerobic fitness levels.

Cardiovascular adaptations

Endurance training increases cardiovascular and thermoregulatory stability during exercise (Convertino, 1991; Cramer et al., 2012; Ekblom et al., 1968; Ho et al., 1997). In older (previously sedentary) participants, physical training decreased T_c and HR during fixed work in the heat, without alterations in body characteristics (Ho et al., 1997). The data indicate that training increased SkBF and plasma volume for the same fixed workload. Endurance training typically increases SkBF for a given T_c and can activate vasodilation for a lower T_c (Beaudin et al., 2009; Roberts et al., 1977; Simmons et al., 2011; Thomas et al., 1999), results not seen with resistance training (Thomas et al., 1999). The increase in SkBF is explained by an expansion of blood volume and increased cardiac output (Simmons et al., 2011), and increases basal production of nitric oxide, an endothelium derived vasodilatory compound(Holowatz and Kenney, 2010; Kingwell et al., 1997).

Sweating adaptations

In addition to the cardiovascular adaptations that are beneficial during hot work, exercise training also enhances sweating function. For instance, endurance training can reduce the T_c threshold for the onset of sweating (Henane et al., 1977; Nadel et al., 1974; Roberts et al., 1977) similar to the effects seen from heat adaptation, but to a lesser extent. Modelling the response based on available literature, Havenith (2001b) suggests that a training-induced increase in $\dot{V}O_{2max}$ by 12-17% will reduce the sweat onset threshold by 0.1°C, although reductions up to 0.4°C have been reported in a low sample size (Henane et al., 1977). With exercise training, there are increases in sweat output for the same T_c increase, in addition to elevations in maximal sweat output (Henane et al., 1977; Nadel et al., 1974; Roberts et al., 1977). Most recently, eight weeks exercise training ($\dot{V}O_{2max}$ increase from 46 to 52 ml/kg/min) increased local sweat rate, and thus skin wettedness from 72 to 85% surface area (Ravanelli et al., 2018). The increased sweating function in the above studies may not be related to aerobic fitness *per-se*, but more due to frequent and persistent rises in T_c due to the training itself, evoking a mild heat adaptation (Ravanelli et al., 2020).

Climate type

At a relative intensity, fitter people had a slower increase in T_c in both cool and hot-dry climates, but a faster increase in T_c in very humid heat (Havenith et al., 1998). Thus, when evaporative heat loss is limited by high humidity, the greater heat produced by fitter people makes them more vulnerable to heat. While a similar study documents equivalent thermoregulatory patterns between trained and untrained males in humid heat (Periard et al., 2012), the water vapour pressure was ~1 kPa higher in the study of Havenith et al. (1998), suggesting an upper critical water vapour pressure where a higher metabolic rate can be compensated for by increasing sweat rates. When fully uncompensable conditions are simulated with NBC clothing, fitness has no impact on thermometric responses (Cheung and McLellan, 1998). The above data suggests that impermeable clothing, or an ambient water vapour pressure of ~4 kPa will likely negate any beneficial effect of aerobic fitness on thermoregulatory function. The true upper threshold will depend on the skin temperature and the evaporative resistance of any clothing ensemble.

Studies using multiple regression

Some studies used multiple regression analysis to determine what variables explain the thermoregulatory responses to heat (Cramer and Jay, 2015; Flouris et al., 2018b; Havenith et al., 1995a, 1998; Notley et al., 2019b). In a temperate environment, the exercising metabolic rate (in W/kg) explained ~50% of the heat storage during fixed intensity exercise, with aerobic fitness explaining only a further 1% (Cramer and Jay, 2015). It is worth noting that this work used forward entry stepwise regression without interpretation of standardised regression coefficients, which are useful when comparing the relative contribution of individuals parameters that have different units. Therefore, the impact of $\dot{V}O_{2max}$ on its own could have been higher 1%. During fixed intensity exercise with dry heat stress, aerobic fitness explained 17-25% of ΔT_c, where there was a negative association (Notley et al., 2019b). In humid heat and at a fixed intensity, T_c was negatively associated with fitness, suggesting that fitness has a protective impact (Havenith et al., 1998). In that study, fitness was poorly associated with heat storage in dry heat, but this is likely because T_c was only mildly elevated in that condition. During fixed intensity work, HR was negatively correlated with absolute VO_{2max} in dry and humid heat stress, indicating that those with a higher fitness level will be less vulnerable to losses in physical work capacity independant of the climate type (Havenith et al., 1995a).

Using ROC curve analysis, it was shown that $\dot{V}O_{2max}$ thresholds of $\leq$ 36.5 and 30 ml·kg^{-1}·min^{-1} be used to identify vulnerable males and females, respectively (Flouris et al., 2018b). Although the fitness requirement for females may be lower, this is explained by the fact they were exercising at a lower absolute heat production. In summary, the impact of fitness on the T_c response is determined by work type (fixed or relative workload) and whether the environment is compensable or uncompensable (see Clarification of terms for definition).

Tolerance to heat

An important consideration with respect to fitness level is the effect this has on heat tolerance since this has implications primarily for work capacity. We define heat tolerance as the maximum exposure duration to hot working conditions, which is dictated by global cardiovascular stress and the T_c rise (Cheung and McLellan, 1998). Compared with unfit adults, fitter individuals ($\dot{V}O_{2max}$ 62 vs 40 ml/kg/min) show a lower HR (~30 b/min) and perceived exertion while cycling at a fixed heat production (Cramer et al., 2012). In the event workers can self-pace, fitter people have an increased physical work capacity for the same HR (Periard et al., 2012). In support, one study found that the ΔT_c was not different between fit and unfit males during uncompensable heat stress, but the fitter individuals had a longer tolerance time, probably explained by their lower HR (Cheung and McLellan, 1998). Another factor relevant to occupational heat stress is that fitter people may have a lower psychological stress for the same rate of heat storage (Tikuisis et al., 2002). A higher fitness level also infers a greater resistance to lipopolysaccharide leakage from the gut (Selkirk et al., 2008), greater cellular tolerance to hyperthermia (Yamada et al., 2008), and a curtailed release of stress hormones (norepinephrine, ACTH) at a given ΔT_c (Wright et al., 2010).

Summary

Aerobic fitness and endurance training can have a strong impact on heat tolerance and is an important factor for determining work capacity and health during hot work. While research points toward improved sweating function with high fitness, the major benefits stem from an increased cardiovascular function. During fixed intensity work, fitness is associated with a lower rate of heat storage and improved cardiovascular stability. During relative intensity (self-paced) work, fitter people can work harder for an equivalent HR and perceived effort compared with unfit people. Working at a relative intensity (i.e. based on fitness) may elevate the risk of hyperthermia in fitter people if evaporation is impeded by high humidity or protective clothing. The heat stress responses in fit vs unfit people are shown in Table 5.

Practical advice

- For fixed paced physical work in the heat, fitter people will typically be at reduced risk of hyperthermia and productivity loss.

- The benefits of fitness on core temperature will be minimised, and even reversed, during uncompensable heat stress i.e. with heavy protective clothing, or in very humid environments (~ 4 kPa). Even in those conditions, cardiovascular stability, and overall tolerance is likely to be improved with high fitness.

- For self-paced physical work in the heat, fitter people will typically have higher work output, but this could lead to a higher T_c if workers are unacclimatised or inexperienced. Monitoring of all workers is recommended regardless of fitness level.

- During heavy work, those with a $\dot{V}O_{2max}$ (ml/kg/min) < 36.5 are more at risk of a higher T_c than those above this threshold.

- During moderate work, those with a $\dot{V}O_{2max}$ (ml/kg/min) < 30 are more at risk of a higher T_c than those above this threshold.

Table 5. Overview of data relating to the effect of aerobic fitness and training on the heat stress response.

Source	Design	n	Condition	Work-type	$\dot{V}O_{2max}$ (ml/kg/min)	Difference in $\dot{V}O_{2max}$	Sweat threshold (°C)	Baseline Core temperature (°C)	Peak Core temperature (°C)	Cardiovascular strain
(Nadel et al., 1974)	Training studies (*within subjects).*	6	23.5°C	15 min cycling at 60% $\dot{V}O_{2max}$	45 vs 38	17%	↓ 0.20	-	-	-
(Henane et al., 1977)	Sweat threshold test pre and post training	3	30°C/40% to 45°C/24% (i.e. 6°C/min^{-1})	Passive heating for sweating tests	48 vs 41	↑ 18%	↓ 0.1-0.4	↓ 0.40	NS	-
(Drinkwater et al., 1976)	Independent groups	12	28°C/45%	100 min walking at 30% $\dot{V}O_{2max}$	49 vs 40	↑ 23%	-	NS	NS	NS
			35°C/65%							
			48°C/10%	50 min walking at 30% $\dot{V}O_{2max}$						
(Houmard et al., 1990)	Training study (*within subjects).* Heat tolerance test pre and post training	9	40°C/27%	90 min walking or jogging at 50% $\dot{V}O_{2max}$	58. No increase from training.	0%	-	-	NS	↓ with training. Final heart rate 10 b/min less
(Cheung and McLellan, 1998)	Independent groups. Subjects donned NBC clothing	15	40°C/30%.	60 min walk at 3.5 km/h^{-1}	60 vs 46	↑ 30%	-	NS	NS	↓ in the fitter group. Final heart rate 10 b/min less despite greater tolerance time
(Jay et al., 2011)	Independent groups	14	24°C/24%	Cycling at 60% $\dot{V}O_{2peak}$	40 vs 60	↑ 49%	↓ 0.40	↓ 0.30	↑ 0.54	-
				Cycling at ~276 W/m^2			↓ 0.30	↓ 0.20	NS	-

(Periard et al., 2012)	Independent groups	16	40°C/50%	Cycling at 60% $\dot{V}O_{2max}$	4 vs 5 l/min	↑ 25%	-	-	NS.	NS
(Cramer et al., 2012)	Independent groups	21	24°C/30%	Cycling at 60% $\dot{V}O_{2max}$ for 60 min	40 vs 62	↑ 55%	-	↓ 0.30	↑ 0.55	NS
(Ravanelli et al., 2018)	Training study	8	38°C/65%	Passive exposure. Humidity ramp protocol	46 vs 52	↑ 14%	-	↓ 0.30	↓ 0.20	↓ with training. Average HR ↓ by 10 b/min

HR; Heart rate; b/min, heart beats per minute; n, number of subjects; $\dot{V}O_{2max}$, maximal oxygen consumption; W/m^{-2}, Watts per metres squared; NS, not statistically significant; T_c, core body temperature; ↑, increased; ↓ decreased; -, not reported.

Heat adaptation

When body tissues are repeatedly exposed to a higher temperature than normal, they adapt to that stress so they can better cope with the physiological demand during future exposures. Adaptation to heat is a reversible phenomenon which begins at a genetic level, manifests to a cellular level, and eventually results in whole body physiological adaptations. Knowledge pertaining to the cardiovascular (Périard et al., 2016; Taylor, 2014), epigenetic (Horowitz, 2016; Horowitz et al., 2014), and performance (Périard et al., 2015; Tyler et al., 2016) adaptations to heat acclimation have been reported in considerable depth. The reader is also directed to an article describing the early use and development of natural (acclimatisation) and artificial (acclimation) adaptation in the mining industry (Schneider, 2016), since it has specific occupational relevance. In this section, we provide a summary of the most relevant information which can inform guidance.

A historical view of heat adaptation

Scientific appreciation of man's adaptability to heat can be traced back to 1768. Observing the adaptability of European's to hot climates, James Lind remarks on behavioural adaptations such as reduced appetite, and changing exposure time by seeking *"repose"* during the heat of the day (Lind, 1768). However, it was not until the early 20th century where the study of man's physiological response to heat adaptation emerged. The following studies form most of the fundamental knowledge in this area (Dill et al., 1938; Eichna et al., 1945; Hellon et al., 1956a; Henschel et al., 1943; Ladell, 1951; Piwonka et al., 1965; Piwonka and Robinson, 1967; Robinson et al., 1943, 1965; Shaklee, 1917; Wyndham, 1951; Wyndham and Jacobs, 1957). In 1917, Alfred Shaklee published a report on the adaptability of monkeys to heat exposure, and postulated that "*If the monkey can become adapted to life in the tropical sun, man could more readily become adapted"* (Shaklee, 1917). He found that the rectal temperature of monkeys exposed to heat was ≥40ºC (and sometimes fatal) for the first two weeks but was always <40ºC for the next 5 months of heat exposure, indicating that most adaptation occurs in the first two weeks. He went on to study his own adaptation to heat over a period of six months and concluded anecdotally that "*Healthy white men may be more readily acclimatized to the conditions named, that is, to the tropical climate at its worst."* On that note, potential adaptability to heat does not depend on ethnic origin (Taylor, 2014). In the 1930's, evidence of decreased sweat-induced ion loss throughout the course of heat exposures was one of the first seminal findings (Dill et al., 1933, 1938). Increased ion reabsorption from sweat glands results in more dilute sweat (Chinevere et al., 2008), which reduces the risk of health issues linked to electrolyte depletion. In the 1940's, evidence of decreased physiological throughout the course of heat adaptation began to emerge, which is linked to increased sweat rates, and decreased HR and T_c (Henschel et al., 1943; Horvath and Shelley, 1946; Robinson et al., 1943). That work used fixed work rates throughout the daily exposures, and generally found that the work was less taxing on the thermoregulatory and cardiovascular system as acquired heat tolerance developed. Henschel et al. (1943) also found the decay of acquired heat adaptation was ~3 weeks, a notion supported by modern-day literature. In the 1950's, more precise data on the adaptation of the sweat rate/T_c relation, as well as the cardiovascular adaptations, such as skin and central blood flow, and cardiac output, which ultimately leads to a reduced HR, began to emerge (Ladell, 1951; Wyndham, 1951; Wyndham et al., 1954b; Wyndham and Jacobs, 1957). After the 1960's, the individual variation in human adaptability to heat was explored. Generally, the scope for heat adaptation does not seem to depend on chronological age (Robinson et al., 1965; Wagner et al., 1972), sex (Frye et al., 1982; Hertig et al., 1963), or physical fitness (Cheung and McLellan, 1998; Piwonka and Robinson, 1967). This concept is highly relevant to occupational heat exposure because most types of people can physiologically adapt to work in the heat.

Physiological adaptations

The extent to which an individual has become heat adapted can be determined through changes in specific physiological, behavioural, and biochemical characteristics. Periard et al. (2015) summarised twenty-five physiological adaptations which occur throughout heat acclimation and the time course for their attainment. Familiar indices include a lower exercising HR, T_c and T_{sk} at rest and during exercise, an earlier sweating onset and an increased sweat rate for a given T_c (Havenith, 2001b). A

plasma volume expansion is a major adaptation which typically peaks after the first week of acclimation (Périard et al., 2016). This adaptation improves cardiovascular stability by increasing vascular filling pressure (Senay et al., 1976) and the specific heat content of blood (Blake et al., 2000). These physiological adaptations allow for improved work performance and comfort during heat stress (Burk et al., 2012; Cheung and McLellan, 1998; James et al., 2017; Lorenzo et al., 2010; Willmott et al., 2016). In support, an early study showed that the risk of syncope during physical work in the heat was due to excessive global cardiovascular strain, but the risk declined throughout the course of acclimation (Eichna et al., 1945). Modelling the sweating adaptation, Havenith (2001b) calculated that acclimation has beneficial effects in terms of i) reducing sweating onset threshold, and ii) it can increase the maximum sweat output for the same T_c (see Table 6). Recent work also shows a redistribution of sweat rate towards the limbs, compared to the torso and back with heat acclimation (Smith and Havenith, 2019). Importantly, in an environment which impedes sweat evaporation (i.e. with NBC clothing), heat acclimatised people will typically lose more sweat for the same rate of heat storage, accelerating dehydration (Cheung and McLellan, 1998; Wyndham et al., 1954a).

Time course of adaptation and decay

Heat acclimation programmes are normally prescribed as short (< 7 days), medium (8-12 days) or long (> 14 days) durations (Garrett et al., 2011). Generally, the reductions in baseline and exercising T_c, T_{sk}, and HR occur after only 4-6 days, while a full adaptation of the sweating response requires ~12-14 days (Périard et al., 2015). Consequently, the ergogenic effects are maximised in line with improvements in the sweating function, owing to greater skin wetness, and an elevated E_{max} (Fox et al., 1964). The time-course for the decay of heat acclimation has been addressed in several reviews (Armstrong and Maresh, 1991; Daanen et al., 2018; Garrett et al., 2011; Pandolf, 1998). After a heat acclimation, studies suggest that the adaptations to HR and T_c are lost at a rate of ~2.5% per day of absence from the heat (Daanen et al., 2018). The general conclusion is that humans return to a pre-acclimation phenotype within 3-weeks of absence from the heat, characterised by a return of sweating responses back to baseline levels (Armstrong and Maresh, 1991; Poirier et al., 2015). Following short-term (5-day) heat acclimation, adaptations to exercising HR and T_c were maintained after one week but lost after two weeks (Garrett et al., 2009). Isothermic protocols ensure the participant's T_c is consistent throughout the programme, which is preferable to a constant daily work rate. Full adaptation may take place a while after the heat acclimation programme itself, as shown by lower resting T_c by ~0.5°C, 6 days after a nine-day programme (Daanen et al., 2011). As observed in the German coal mines, new workers should be paired with a more experienced worker during the initial days of exposure to learn optimal pacing and drinking behaviours (Kalkowsky and Kampmann, 2006). Early work demonstrates a memory feature with heat adaptation, since pre-acclimatised workers took only two days to return to an acclimatised phenotype after a 6-day period of working in cool conditions (Wyndham and Jacobs, 1957). Furthermore, Weller (2007) showed that only 2 and 4 days of heat acclimation was required for re-acclimation following 12 and 26 days of non-exposure to heat stress, respectively. A recent systematic review and meta-analysis showed that heat-reacclimation occurs 8-12 times faster than the process of heat acclimation decay (Daanen et al., 2018). In practical terms, this means that heat acclimation can be maintained relatively simply in workers who have previously undergone a recent procedure of heat acclimation.

Summary

Adaptation to heat can have a strong impact on the heat stress response, inferring a physiological advantage when sweat evaporation is possible. Strong evidence supports that short-term heat acclimation (< 7 days) is beneficial for those required to work in heat stress conditions, reflected by a lower T_c and HR compared with pre-acclimation. Long-term heat acclimation (> 14 days) provides further benefit due to adaptation of the sweating mechanism and acquired cellular tolerance to hyperthermia. Evidence of heat acclimation memory suggests that a rapid re-acclimation is likely in individuals previously exposed to long-term heat acclimation. The heat stress responses in non-acclimated and acclimated individuals are shown in Table 6.

Practical advice

Advice for natural adaptation:

- Natural acclimatisation to hot work will typically occur over 14-30 days.
- Unacclimatised workers should be considered more at risk and be monitored frequently during acclimatisation.
- New workers will typically benefit from working with someone more experienced during acclimatisation.
- New workers should try to adopt similar fluid replacement behaviours and pacing strategies to more experienced workers.

Advice for laboratory/artificial adaptation:

- Acclimation should be 5-days minimum, with full adaptation taking place over 14-days.
- Adaptations to heat will be lost after ~3 weeks no heat exposure, but re-acclimatisation will typically only take 3-4 days i.e. workers do not have to go through the full 14-day process twice.

General considerations:

- The positive effect of acclimation/acclimatisation will be lower if sweat evaporation is impeded with impermeable protective clothing, or in very humid environments.
- Acclimation/acclimatization increases sweat output, so may result in greater body fluid losses, especially in severe environments, such as those noted above.

Table 6. Overview of data relating to the effect of acclimation on the heat stress response. Participants are young adult males, unless stated otherwise.

Source	Participants (n)	Acclimation duration & environment.	Daily protocol/test of acclimation status	Sweat rate	Baseline Core temperature (°C)	Peak Core temperature (°C)	Sweat threshold (°C)	Cardiovascular strain
(Robinson et al., 1943)	Young adult (5)	10-23 days. 40°C/23%	Treadmill walking at 5.6 km/h at ~ 5% incline for 60 to 240 min	↑ 25%	-	↓ 1°C	-	↓ ~28 b/min
(Wyndham, 1951)	13 vs 353 non acclimated.	2-3 weeks. ~47°C, 20%	12 steps/min for 2.5 hours (30 min work, 30 min rest)	↑ 54%	-	↓ ~0.20 – 0.5°C	-	↓ ~26 b/min
(Ladell, 1951)	Young adult (17)	9 days. 38°C/77%	12-24 steps/min for 2.5 hours (5 min work, 15 min rest)	↑ 48%	↓ 0.29°C	↓ 0.36°C	↓ 0.13°C	↓ ~10 b/min
(Hertig et al., 1963)	Young adult females (5)	10 days at 45°C/20%	Treadmill walking at 4.8 km/h for 2 hours	↑ 27%	-	↓ 0.9°C	-	↓ ~35 b/min
	Young adult females (4)	10 days at 45°C/50%	Treadmill walking at 5.6 km/h for 2 hours	↑ 15%	-	↓ 0.6°C	-	↓ ~15 b/min
(Robinson et al., 1965)	Older (4)	5-13 days. 50°C/23%	Treadmill walking at 5.6 km/h at ~ 5% incline for 65 to 85 min	↑ 12%	-	↓ 0.9°C	-	↓ ~35 b/min
(Garden et al., 1966)	Young adult (12)	9 days. 36°C/80%	Treadmill walking at 5.6 km/h for 50 min	↑ 17%	NS	NS	-	NS
	Young adult (13)	9 days. 36°C/80%	Treadmill walking at 5.6 km/h for 80 min	↑ 21%	↓ 0.31°C	↓ 0.35°C	-	↓ ~15 b/min
	Young adult (13)	9 days. 36°C/80%	Treadmill walking at 5.6 km/h for 100 min	↑ 25%	↓ 0.32°C	↓ 0.2°C	-	↓ ~10 b/min
(Piwonka and Robinson, 1967)	Young adults of high fitness (5)	5 days. 50°C/15-20%	5.6 km/h at ~ 5.6% incline for 85 min	↑ 11%	-	↓ 0.2°C	-	↓ ~20 b/min
(Gonzalez et al., 1974)	Young adult (6)	6 days. 40°C/39%	Cycling at 25% $\dot{V}O_{2max}$ for 40 mins	↑ 40%	↓ ~0.15°C	↓ ~0.4°C	↓ 0.5°C	↓ ~5-10 b/min

(Henane and Bittel, 1975)	Young adult (12)	9 days. 45°C, 24%	Passive exposure at 45°C, 24%	↑ 24%	↓ 0.30°C	↓ ~0.40°C	↓ 0.27°C	-
(Havenith and van Middendorp, 1986)	Young adult, mixed fitness (4)	7 days. 40°C, 20%	Work/rest cycling to regulate T_c at 38.3°C for 2 hours	↑ 18%	-	↓ 0.25°C	↓ 0.5°C	↓ ~10-14 b/min
(Cheung and McLellan, 1998)	Young adult, moderate fitness (7)	5 days per week for 2 weeks i.e. 10 sessions at 40°C/20%	Walking at 40°C/20%. Fully uncompensable due to clothing	↑ 28%	NS	NS	-	↓ ~8 b/min
	Young adult, high fitness (8)			↑ 17%	NS	NS	-	↓ ~10 b/min
(Inoue et al., 1999)	Young adult, moderate fitness (5)	8 days at 43°C/30%	Cycling at 35% $\dot{V}O_{2max}$ for 90 mins	NS	-	↓ 0.30°C	-	%HRmax ↓ by ~10% in all groups
	Older, high fitness (4)					↓ 0.40°C	-	
	Older, low fitness (5)					↓ 0.50°C	-	
(Garrett et al., 2009)	Young adult, moderate fitness (10)	5 days at 39.5°C/60%	Cycling at 40% peak power output in 35°C/60%	-	NS	↓ 0.30°C	-	↓ ~13 b/min
Daanen et al. 2011 (Daanen et al., 2011)	Young adult, high fitness (15)	9 days at 35°C/29%. Then 3 days at 41°C/33%	Cycling at 45% $\dot{V}O_{2max}$ for 60 mins	NS	↓ 0.12°C	↓ 0.17°C	-	↓ ~10 b/min
(Gibson et al., 2015)	Young adult, moderate fitness (8)	5 days at 40°C/39%	Cycling at 50% $\dot{V}O_{2peak}$ for 90 mins	↑ 23%	↓ 0.29°C	NS	-	↓ ~9 b/min
	Young adult, moderate fitness (8)	10 days at 40°C/39%		↑ 32%	↓ 0.33°C	NS	-	↓ ~8 b/min
	Young adult, moderate fitness (8)	5 days at 40°C/39%	Cycling at 65% $\dot{V}O_{2peak}$ until T_c reached 38.5°C. Work/rest then adjusted to keep T_c constant	↑ 17%	NS	NS	-	↓ ~12 b/min
	Young adult, moderate fitness (8)	10 days at 40°C/39%		↑ 26%	↓ 0.09°C	NS	-	↓ ~11 b/min

b/min, heart beats per minute; n, number of subjects; $\dot{V}O_{2max}$, maximal oxygen consumption; NS, not statistically significant; T_c, core body temperature; ↑, increased; ↓ decreased; -, not reported.

Ageing

Ageing is accompanied by several physiological changes which are relevant to human heat stress vulnerability. In general, the changes are maladaptive for thermoregulation, and include a hampered cardiovascular function (Betik and Hepple, 2008; Minson et al., 1998), sweat gland output (Anderson and Kenney, 1987; Hellon and Lind, 1956; Kenney and Fowler, 1988) and reduced thermal perceptual sensitivity (Coull et al., 2017; Dufour and Candas, 2007; Inoue et al., 2016). While there is overwhelming evidence that pre-frail and frail elderly people account for most of the mortality/morbidity statistics during heat waves (Kenney et al., 2014), the relative impact of age on heat stress responses to physical work needs a general clarification, especially as the effective retirement age in most countries has been rising since 2000. Compared with young adults, ageing has been shown to reduce heat loss capacity as early as age 40, primarily through a reduction in whole-body sweat losses for certain work-loads (Larose et al., 2013). These findings help explain the documented link between age and heat stroke risk in Bantu miners (Strydom, 1971). Analysis from that work showed those over the age of 40 accounted for over 50% of fatal heat stroke and 25% of nonfatal heat stroke cases, despite accounting for less than 10% of the total working population (Strydom, 1971).

Cardiovascular maladaptation with age

Seminal work in the 1960's showed that sustained increases in skin temperature can result in a doubling of cardiac output and resting HR (Rowell et al., 1969). Responses like this, which are accompanied by large reductions in peripheral resistance, cause a re-distribution of blood flow from the core to the cutaneous vascular beds for heat dissipation (Rowell et al., 1969). Since that work, numerous studies compared responses of young and older adults to heat stress. During passive, uncompensable heat stress, elderly people (aged ≥ 65 years) showed a 33% reduction in stroke volume and cardiac output, accounting for 53% reduction in total SkBF compared with young adults (Minson et al., 1998). That healthy ageing reduces stroke volume is not a consistent finding however (Gagnon et al., 2016), and the explanation for the disparity between studies remains unclear. With advancing age, many studies have shown that vasoreactivity is reduced during heat stress (Holowatz et al., 2003; Stanhewicz et al., 2015, 2017). Nitric oxide is an important vasodilatory molecule but its concentration within the endothelium is reduced in older people, an effect which contributes to decreased SkBF (Holowatz et al., 2006). While folic acid supplementation may potentially rescue some of the age-related declines in vasoreactivity (Stanhewicz et al., 2017), 6-weeks supplementation had no impact on SkBF or T_c during whole body heat stress in older adults (Gagnon et al., 2018). The above data pertains to elderly individuals, and as such cardiovascular perturbations are likely to be present but less severe in healthy workers < 60 years of age.

Matched groups

An early study compared heat stress responses in young (19-31) and older (39-45) miners who performed stepping exercise over 4 hours (Hellon et al., 1956b). The authors found similar T_c responses the first 3-hours, after which the T_c was only 0.3°C higher in the older group. There were greater levels of cardiovascular strain in the older adults, marked by a 10 b·min^{-1} higher HR during work from 40 min to the end of the trial. Consequently, the older adults worked closer to their age-predicted maximum HR by ~14%.

In the last decade, numerous studies have compared heat stress responses in well-matched participants of different age groups (Anderson and Kenney, 1987; Kenney, 1988; Kenney and Anderson, 1988; Kenny et al., 2017; Larose et al., 2013, 2014; Stapleton et al., 2015; Tankersley et al., 1991). In dry heat, older people store more heat due to reductions in evaporative heat loss, but the difference is proportional to the metabolic heat load. At heat loads >325 W, sweat evaporation was reduced by ~14% in those aged 58 compared with well-matched young adults in a hot dry environment (Stapleton et al., 2015). This resulted in greater levels of whole-body heat storage, and an increased T_c. During cycling at 400 W, age-related decrements in sweat loss occurred as early as age 40 compared with

young adults (Larose et al., 2013). In summary, there is an independent negative impact of age on sweat evaporation and heat storage during exercise in fully compensable environments.

High humidity decreases the proportion of sweat that evaporates into the environment to provide a cooling effect (Candas et al., 1979). Intuitively, there is less likely to be a different thermoregulatory response to humid heat between age groups, because young people cannot take advantage of their higher sweat rates. Indeed, at low to moderate intensity exercise, the difference in T_c between young and older groups is minimal in high humidity (Havenith et al., 1995b; Kenney, 1988; Kenney and Anderson, 1988; Larose et al., 2014; Tankersley et al., 1991), peaking at around ~0.4ºC after 1.5-2 hours work (Kenney, 1988). However, studies do find blunted cardiovascular effector responses in older people during humid heat, such as reduced SkBF and cardiac output (Havenith et al., 1995b; Kenney, 1988; Tankersley et al., 1991). The maintenance of SkBF is particularly relevant for dry heat transfer, especially if ambient temperature < skin temperature.

Population averages

Compared with study designs that match young and old for all relevant characteristics, using unmatched participants better reflects the differences between age groups on a population level.

Fixed work rate

Havenith et al. (1995) documented the relative importance of age compared with $\dot{V}O_{2max}$, anthropometry, and adiposity on thermoregulatory and cardiovascular responses during cycling in humid heat, at equal absolute work rate. They showed that $\dot{V}O_{2max}$, body mass and body surface area predicted the T_c and whole body sweat losses during exercise, but age did not. However, age *was* a strong predictor of the cardiovascular responses to humid heat, particularly SkBF which was lower with age, despite similar levels of cardiovascular strain (%HR_{max}). While fitness ($\dot{V}O_{2max}$ in L/min) was the primary indicator of HR, ageing further reduced working HR in a nonlinear fashion (Havenith et al., 1995b), likely due reduced beta-adrenergic responsiveness, calcium handling, and myocyte counts (Olivetti et al., 1991). The ageing mediated reduction in HR and SkBF is due to structural and functional changes in the heart and cutaneous vasculature. Notable cardiac changes include reduced beta-adrenergic responsiveness, calcium handling, and myocyte counts (Olivetti et al., 1991). Age-related changes in vasodilatory function were described above. In the study of Havenith *et al* (1995b), older people were working at a similar percentage of maximum HR compared with young adults of the same fitness level. Regardless of age, the fitness level was the main determinant of cardiac strain, in terms of both absolute HR and %HR maximum.

Relative work rate

Several studies have used an exercise intensity relative to fitness (i.e. %$\dot{V}O_{2max}$) to compare thermometric and cardiovascular responses between unmatched young and older adults. Due to reduced fitness level, metabolic rate is normally lower in the older groups, meaning they produce less metabolic heat. Despite this reduced heat production, the negative ageing effect on thermoregulatory function can result in similar *rates* of T_c rise in young and older people, despite the lower heat production in older individuals (Inbar et al., 2004; Tankersley et al., 1991). Consequently, working at a relative intensity yields a similar percentage of maximum HR across age groups, indicating that self-pacing can result in equivalent thermoregulatory and cardiovascular loads between age groups (Tankersley et al., 1991). In terms of protection from hyperthermia, the effectiveness of self-pacing will depend on the heat severity of the climate. Self-pacing may be less effective in uncompensable (high humidity) conditions, since required sweat evaporation for heat balance will typically be high regardless of any reduction of metabolic heat load (Dufour and Candas, 2007; Kenny et al., 2017; Sagawa et al., 1988). In less extreme, compensable conditions, self-pacing seems to be a good measure to prevent hyperthermia in older workers (Kalkowsky and Kampmann, 2006).

Heat tolerance

Tolerance times to heat are closely related to fitness (Cheung and McLellan, 1998), which is of relevance in this section because i) young participants are generally more fit than aged participants (Betik and Hepple, 2008), and ii) exercise training will infer greater tolerance to heat in an older

population (Ho et al., 1997). On a population level, older people appear to be less vulnerable to heat if they work at an intensity relative to their fitness. At a fixed exercise intensity, older people are more vulnerable to heat on a population level. Using ROC curve analysis, Flouris et al. (2018b) show that age is a predictor of the heat stress response to fixed pace exercise. For heavy work in males, they suggest those over the age of 52 years are more likely to have a higher T_c than those below this age. For females performing moderate intensity work, they suggest a threshold of 56 years.

Summary

Age can have a strong impact on the heat stress response on a population level, but this is primarily linked to reduced cardiovascular fitness. In matched groups, age has a moderate impact on the heat stress response. While exercise training in older people helps maintain cardiovascular responses to heat, reductions in sweat output are apparent at moderate to high heat loads. In a compensable environment, older people are expected to show lower levels of sweat evaporation, and thus a higher level of heat gain at moderate to heavy workloads. In an uncompensable environment, younger people cannot take advantage of a greater delivery of heat to the skin surface for cooling and may store heat at the same rate as older people. In general, absolute $\dot{V}O_{2max}$ peaks at ~20-29 years and declines as a function of age thereafter. Because tolerance to heat is largely dependent on the aerobic fitness level, one can expect a reduced performance in the older workforce. If older people can self-pace, the risk does not appear to be significant. Comparative heat stress responses between young and older people are shown in Table 7.

Practical advice

- For fixed paced physical work in the heat, older people are more vulnerable to hyperthermia and reduced physical work capacity.

- If self-pacing is allowed, there should be no greater risk in older people compared with young people, if the workload is not heavy (see Table 1), and if the environmental heat is not extreme.

- Those over the age of 50 should be monitored closely upon initial exposure to heat stress. Those under this age are typically at less risk of heat injury.

Table 7. Overview of data relating to the effect of age on the heat stress response.

Source	n	Younger group age (y)	Older group age (y)	Fitness matched ?	Condition (s)	Work-type	Sweat rate	Baseline Core temperature (°C)	Peak Core temperature (°C)	Cardiovascular strain
(Hellon et al., 1956b)	36	19-31	39-45	No	38°C/52%	Step exercise with work/rest cycles	↓ 30%	↓ 0.1°C	↑ 0.2°C	↑ by ~10 b/min throughout the work /rest cycles
(Lind et al., 1970)	12	22-31	39-53	No	25°C/64%	8-hour exposure comprising work/rest cycles. Activity simulated manual labour	↓ 4% (NS)	-	↑ 0.1°C	Absolute heart rate higher in young, but $\%HR_{max}$ similar
					36°C/64%		↓ 8% (NS)	-	↑ 0.23°C	
(Drinkwater and Horvath, 1979)	38	12-68 (heterogeneous sample of women). 20 vs 60 year olds used in this table		No	28°C/45%	Walking at 30-35% $\dot{V}O_{2max}$	NS	-	NS	Final $\%HR_{max}$ ↑ by ~5-10% in all 3 conditions
					35°C/65%		↓ 33%	-	↑ 0.3°C	
					48°C/10%		↓ 14%	-	NS	
(Drinkwater et al., 1982)	20	38 ± 2	57 ± 2	No	40°C/30%	Passive exposure	NS	NS	NS	NS
(Anderson and Kenney, 1987)	16	20-30	52-62	Yes	48°C/14%	Walking at 40% $\dot{V}O_{2max}$	↓ 22%	NS	↑ 0.4°C	NS
(Kenney and Anderson, 1988)	16	20-30	52-62	Yes	37°C/60%	Walking at 40% $\dot{V}O_{2max}$	NS	NS	↑ 0.4°C	NS
(Tankersley et al., 1991)	13	24-30	58-74	Yes	30°C/55%	Cycling at 65% $\dot{V}O_{2max}$	NS	NS	NS	NS

							See paper for regression equations			
(Havenith et al., 1995b)	56	20-73 (heterogeneous sample)		Yes	35°C/80%	Cycling at heat production of 300 W	Related to $\dot{V}O_{2max,}$ not age.	-	Related to $\dot{V}O_{2max,}$ not age.	Related to age and $\dot{V}O_{2max.}$
(Inbar et al., 2004)	16	23 ± 0.8	71 ± 1	No	41°C/21%	Cycling at 50% $\dot{V}O_{2peak}$	-	↓ 0.5°C	NS	↓ 20%
(Larose et al., 2013)	85	20-31	50-55	Yes	35°C/20%	Cycling at heat production of 400 W	↓ 9%	↓ 0.08°C	NS	-
(Stapleton et al., 2015)	20	21 ± 1	48 ± 5	No	40°C/15%	Cycling at heat production 300, 400, and 500 W	NS	NS	↑ 0.7°C	↑ 22% (only at 500 W)
			49 ± 5	Yes			NS	NS	NS	NS
(Kenny et al., 2017)	60	19-28	55-73	No	44°C, 30%	Passive exposure	↓ 27% (only at thigh)	-	↑ 0.2°C	$\%HR_{max}$ ↑ by ~10%

HR; Heart rate; b/min, heart beats per minute; n, number of subjects; $\dot{V}O_{2max}$, maximal oxygen consumption; W/m^{-2}, Watts per metres squared; y, years; NS, not statistically significant; T_c, core body temperature; ↑, increased; ↓ decreased; -, not reported.

Sex

There are several factors relevant to thermoregulation that may differ between males and females. Studies on large subject numbers show that compared with males, females on average have a lower body mass and lower cardiorespiratory fitness (Kaminsky et al., 2015). In prior sections, these factors were shown to have a strong influence on heat stress vulnerability. Sex differences in thermoregulation have been reviewed previously (Burse, 1979; Havenith, 1985; Kaciuba-Uscilko and Grucza, 2001; Kenney, 1985), but there have been significant advances in this subfield in the last two decades, which are well summarised in a more recent review (Gagnon and Kenny, 2012a). The general conclusions from prior work are that males and females are mostly equal in thermoregulatory control if fitness and body composition are equal, despite small differences in sweat rates. This section will provide an update on the current state of knowledge regarding sex differences in heat stress responses.

Population averages

Early studies document the comparative responses of unmatched men and women to various types of heat exposures, representing population averages. The earliest comparisons were made in the 1940's, documenting differential heat stress responses between men and women at rest (Hardy and Du Bois, 1940). Further comparisons demonstrate a delayed sweating onset and a reduction in maximum sweat rates in females (Bittel and Henane, 1975). During physical work, the impact of sex on the heat stress response seems to depend on the environment, fitness, and status of heat adaptation. During physical work in the heat, women initially suffered from greater T_c's and HR, but the differences subsided following a period of acclimation (Wyndham et al., 1965). In that study, the lighter mass for the women likely contributed to the faster rate of heat gain initially, while their greater sweating with heat adaptation later compensated (Havenith, 2001a). Using multiple regression, Havenith showed that gender was a predictor of the T_c response in dry and humid heat, but lost its predictive power when $\dot{V}O_{2max}$ and body characteristics were added into the model (Havenith and van Middendorp, 1990). Therefore, the effect of sex as an independent variable is minimal in comparison to fitness and body characteristics. In unmatched participants, a heavy work rate caused a faster increase in T_c and HR in females compared with males (Gagnon et al., 2009). In that study, the increased heat vulnerability of the females is explained primarily by their lower body mass, but their lower fitness may have also contributed. On a population level, sex impacts heat vulnerability, owing primarily to the differences in fitness and body characteristics (Gagnon et al., 2009; Havenith and van Middendorp, 1990).

Evidence shows a reduced sweat output in females compared with males. Women have been shown to exert sweat rates as low as 30% to that of males, with the differences increasing as a function of the heat stress severity (Gagnon and Kenny, 2012b; Hardy and Du Bois, 1940; Hertig, 1971; Notley et al., 2017; Wyndham et al., 1965). Importantly, large differences in sweat output can also be due to women working at a lower rate of heat production during relative intensity work, due to their lower fitness level (Smith and Havenith, 2012). The importance of a lower sweat rate depends on the environmental humidity. In a dry environment, women typically show higher rates of T_c rise than men due to their reduced sweat evaporation (Frye and Kamon, 1981; Shapiro et al., 1980). However, greater sweat rates in males can cause a higher T_c and HR in uncompensable environments, due to faster rates of dehydration (Avellini et al., 1980; Havenith, 1985; Kenney, 1985; Shapiro et al., 1980). Importantly, the differences in sweat output between males and females are abolished after heat acclimation (Frye and Kamon, 1981).

Matched individuals

Compared with females of equal fitness, males showed a greater sweat rate and a lower T_c rise during treadmill walking in extreme dry heat at the same relative intensity (Frye and Kamon, 1981). The females also showed a greater HR in that study by 10-15 b·min^{-1}, implying reduced physical work capacity during self-paced work. It is important to note that the sexes were only matched for fitness, not size, such that the males had a greater body mass and surface area, which are protective against rises in T_c and HR (Havenith et al., 1995a; Havenith and van Middendorp, 1990). However, the

differences were abolished once both groups were acclimated. Cycling at a heat production of 500 W in dry heat, females matched for body characteristics and fitness had a lower sweat output for a given change in body temperature (Gagnon and Kenny, 2011). Here, the males activated heat loss responses (evaporation and cutaneous blood flow) at a lower body temperature compared with females, resulting in a lower end-exercise T_c. The mechanism behind these responses are not fully elucidated, but recent evidence suggests that this may be due to differences in maximal sweat gland output (Gagnon et al., 2013a). Females seem to have a lower maximum sweat gland output compared with males, which means they compensate by activating a greater quantity of sweat glands. When the activated number of sweat glands reaches its maximum (i.e. a mean body temperature increase of ~1°C), the higher maximal sweat gland output in males elevates sweat rate for the same mean body temperature (Gagnon et al., 2013a; Gagnon and Kenny, 2012b). An independent effect of sex on the heat stress response may only appear at heat loads > 250 $W \cdot m^{-2}$ (Gagnon and Kenny, 2012b).

Menstrual cycle

There are detectable differences in T_c throughout the menstrual cycle, specifically between the pre- and post-ovulation phases. Since the thermogenic hormone progesterone is released subsequent to ovulation, there is typically an increase in resting baseline T_c of ~0.5°C (Kenshalo, 1966). Many studies were conducted in the late 1960's to determine the impact of the menstruation on the heat stress response. Early work was equivocal, either finding a lower T_c "set-point" for the onset of sweating pre-ovulation (Bittel and Henane, 1975; Haslag and Hertzman, 1965; Stephenson and Kolka, 1985), or finding no meaningful differences in the T_c and sweat relation (Senay, 1973; Wells and Horvath, 1973). Based on a recent analysis, the weight of the evidence suggests that menstrual phase *does* alter the T_c onset thresholds for sweating and vasodilation, with delays up to 0.5ºC in the luteal phase compared with the follicular phase (Charkoudian et al., 2014). Of note, mild rises in T_c have been shown in the luteal phase with combined use of oral contraceptives (Lei et al., 2019). However, measurement of onset thresholds need to be conducted under well-controlled conditions, since their effects are quite small and can be negated by other factors, such as time of day (Stephenson and Kolka, 1985). Also, onset thresholds for vasodilation and sweating are typically conducted in one limb and might well be compensated for in other body areas. Therefore, it is important to consider whole body heat stress responses to physical activity in the heat to determine the true relevance of the menstrual cycle. When the female response to two-hour extreme dry heat was compared at the three menstrual phases, there were no significant differences in T_c, skin temperature, or body heat content (Wells and Horvath, 1973). It was also shown that differences between pre-and post-ovulation are not affected by heat acclimation. During exercise at a fixed rate of heat production, there were no differences in T_c or T_{sk} when women exercised at the follicular or luteal phase of menstruation. Moreover, there were no differences in biophysical parameters such as maximum evaporative potential, required evaporation, and whole-body heat storage (Notley et al., 2019a). In summary, menstrual phase has a marginal impact on the heat stress response and is unlikely to dictate independently whether an individual is vulnerable to heat stress.

Summary

Sex has a moderate impact on the heat stress response which becomes minor if body characteristics and fitness factors are accounted for. The impact of sex on hyperthermia and work capacity are mostly relevant during heavy work in compensable environments. Compared with men of equal fitness and body composition, women may have a higher HR and reduced capacity for sweat evaporation at heavy workloads, but the differences disappear if both groups are heat acclimated. If the heat load is strong enough, this can result in a greater rate of heat storage and thus an elevated T_c in unacclimated females. Menstruation appears to affect resting T_c but does not influence the rate of heat storage or the threshold for sweating onset. The effect of sex on thermoregulatory responses to heat are shown in Table 8.

Practical advice

- On a population scale, males are more suited to hot work compared with females. However, the minimum criteria for hot work should be initially based on fitness and age, not sex.

- Females will typically be more at risk of hyperthermia if the heat load is high (see Table 1).
- Males are likely to dehydrate faster in uncompensable heat stress, due to higher sweat output.
- Once fully acclimatized to the heat, the heat stress response between matched males and females is similar.

Table 8. Overview of data relating to the heat stress responses in women when compared with men.

Source	n	Fitness matched?	Condition	Work-type	Sweat threshold (°C)	Sweat rate	Baseline Core temperature (°C)	Peak Core temperature (°C)	Cardiovascular strain
(Wyndham et al., 1965)	56	No	34°C/90%	Step test at 1 litre/min $\dot{V}O_2$		↓ 30%	NS	↑ 0.4°C	↑ 20 b/min
(Bittel and Henane, 1975)	14	No	45°C/30%	Resting	~5 min onset delay	-	NS	↑ 0.4°C	-
(Havenith and van Middendorp, 1990)	26	Yes	34°C/80% 45°C/20%	Relative intensity cycling	-	See paper below for regression equations There was an effect of gender on the heat stress response, but this was due to differences in body characteristics.			
(Frye and Kamon, 1981)	8	Yes	48°C/14%	Relative intensity cycling. 3 hours at 30% $\dot{V}O_{2max}$	NS	↓ 34%	NS	↑ 0.44°C	↑ 12 b/min
(Gagnon et al., 2009b)	12	No	30°C/30%	Cycling exercise at 500 W	-	-	-	↑ 0.50°C	↑ but no data provided.
(Gagnon and Kenny, 2011)	18	No	35°C/12%	Relative intensity cycling for 90 min. 50% $\dot{V}O_{2max}$	NS	↓ 21%	NS	NS	-
				Fixed intensity cycling for 90 min. Heat production equal to 500 W	NS	↓ 33%	NS	↑ 0.46°C	-

b/min, heart beats per minute; n, number of subjects; $\dot{V}O_{2max}$, maximal oxygen consumption; NS, not statistically significant; ↑, increased; ↓ decreased; -, not reported.

Chronic Health Conditions

Chronic health conditions have an important impact on the human heat stress response. Addressing all health conditions is beyond the scope of this review because our findings are applied to those who perform physical work in the heat. We primarily focus on diabetics due to its current and future global prevalence (Roglic, 2016), and available research investigating its impact on whole body heat stress responses. We discuss hypertension and cardiovascular diseases more briefly because the proportion of the population with clinically relevant hypertension or heart disease performing physical work in the heat is likely to be small, and applies mostly to the elderly population (Kenney et al., 2014). Moreover, research investigating whole body physiological responses to heat in those with these conditions is sparse, and in some cases absent entirely. Nonetheless, understanding the role of cardiovascular disease in vulnerability to heat is relevant for scenarios in which people with these underlying conditions still perform work in the heat.

Diabetes

The World Health Organisation estimates that 422 million adults have diabetes, the majority of which have type 2 diabetes. The global prevalence of diabetes has nearly doubled since 1980, rising from 4.7% to 8.5% of the adult population (Roglic, 2016), and prevalence rates may reach an astonishing 33% by 2050 (Boyle et al., 2010). With diabetes being the most prevalent morbidity present in the population, it is pertinent to address whether thermoregulatory function is impaired in these individuals. We should note that more in-depth reviews are available specific to diabetes and thermoregulation, for the interested reader (Kenny et al., 2016; Yardley et al., 2013). Our aim in this section is to give a concise summary of the primary information of relevance for employers and policymakers.

Local skin blood flow

Thermal physiologists have taken interest in diabetics because local SkBF and sweating are negatively correlated with the level of glucose control (Brugler et al., 2011; Petrofsky et al., 2009; Wigington et al., 2004). At a normal T_c of ~37°C, there is very little difference in SkBF between diabetic and non-diabetic participants, but diabetics have shown up to a 50% reduction in local SkBF stimulated by heat or vasodilatory compounds (Brugler et al., 2011; Fujii et al., 2018; Rendell et al., 1989). The link between diabetes and a reduced SkBF is coined diabetic cutaneous microangiopathy and can affect both type 1 (T1DM) and type 2 (T2DM) diabetes mellitus sufferers. In T1DM, there is no release of C-peptide which is produced in pancreatic β cells, and the peptide has known roles in maintaining microvascular blood flow (Forst et al., 1998; Forst and Kunt, 2004). In T2DM, the reductions in SkBF may be due to a reduced nitric oxide bioavailability (Beer et al., 2008; Williams et al., 1996), which is worsened by the presence of atherosclerotic plaques (Kawashima and Yokoyama, 2004; Watson et al., 2003). There may be additional factors at play, and the interested reader is directed to two reviews for further reading (Kenny et al., 2016; Ngo et al., 2005).

Whole body responses

The above evidence is based on local SkBF measurements with laser Doppler, but until recently it was unknown whether they translate into meaningful whole-body responses. The evidence thus far is equivocal and seems to depend on the severity of the condition and physical fitness of the individual. For instance, young-adult recreationally active T1DM sufferers were compared against well-matched healthy controls during one-hour cycling exercise at 400 W metabolic heat production, and the thermoregulatory responses were similar between both groups (Stapleton et al., 2013). When the heat load was increased to 500 W, T1DM sufferers exhibited lower sweat rates in the forearm and chest, which in turn led to an increased T_c by up to 0.5°C (Carter et al., 2014). The findings were repeated in a later study which showed impaired thermoregulation during exercise in T1DM patients (McGinn et al., 2015). Most recently, a study demonstrated reduced evaporative heat loss and higher T_c in young adults with T1DM but only during heavy work (Notley et al., 2019c). For T2DM sufferers working at a high metabolic rate for 1-hour in mild heat, an increased heat storage rate was documented due to a lower rate of evaporative heat exchange, compared with health matched controls (Kenny et al., 2013).

Overall, it seems that recreationally active diabetes sufferers can show impairments in heat loss if the workload is heavy. Whether or not prolonged work at a lower rate of heat production is dangerous for diabetics has not been investigated.

Cardiovascular disease

Cardiovascular disease is a broad term that can encompass several conditions such as chronic heart failure, coronary and valvular heart disease, cardiomyopathy, congenital heart defects, and cerebrovascular and peripheral vascular disease (Kenny et al., 2010).The majority of deaths during heat waves are attributed to cardiovascular issues, and are predominant in the elderly population (Conti et al., 2005; Kenney et al., 2014). During heat stress, the elevated risk of death in those with cardiovascular disease has been described previously (Kenney et al., 2014). Although risk of death is higher in those with cardiovascular disease, its impact on hyperthermia risk and HR during work in the heat is less clear due to the paucity of evidence. Patients with congestive heart failure had similar T_c and HR responses to passive heat stress compared with healthy controls, despite lower SkBF (Cui et al., 2005). In that study, those in the congestive heart failure group did not discontinue any medication, which we consider a strong reflection of real-world responses. In a later study, it was shown that patients with chronic heart failure showed no difference in T_c and HR, with no reduction in sweat rate, again despite a lower SkBF (Cui et al., 2013). That work used a water perfused suit model which limits most excreted sweat from evaporating, making comparisons in T_c problematic. During 3-hours exposure to mild heat stress in a climatic chamber, those with ischemic heart disease experienced similar thermoregulatory responses to healthy controls (Andersen et al., 1976). During cycling exercise in mild heat, heart failure resulted in a faster T_c rise compared with control participants, either at relative (Balmain et al., 2016) or fixed intensity work (Balmain et al., 2018). The faster increase in T_c was primarily due to a reduced SkBF downstream of attenuated cardiac function, since sweat responses were not different between groups in both studies. Finally, the thermoregulatory responses to physical activity in the heat was not affected by previous coronary artery bypass surgery, compared with healthy controls (Walsh et al., 2002). Overall, cardiovascular disease is not a strong *independent* predictor of the heat stress response in the working population. However, individuals with cardiovascular disease are likely to present with very low fitness levels, which is a major risk factor for hot work.

Hypertension (high blood pressure)

Hypertension is a long-term medical condition characterised by a permanent elevation of peripheral resistance. Hypertension decreases resting SkBF and produces a shallower slope between SkbF and increased T_c (Carberry et al., 1992; Kenney et al., 1984). As noted in the clarification of terms section, such changes in SkBF do not necessarily translate into greater heat vulnerability during physical work. When well matched normotensive and hypertensive participants are compared during physical work in the heat, their T_c and HR responses are similar (Fonseca et al., 2015; Kenney and Kamon, 1984). As noted by Kenny et al., (2010), the use of antihypertensive medications (diuretics, vasodilators, β-blockers) may independently increase susceptibility to heat stress issues. Similarly to cardiovascular disease, hypertension has a marginal *independent* effect on the heat stress response. However, individuals with hypertension are likely to present with lower fitness levels, which is a major risk factor for hot work.

Summary

Diabetes can have a moderate impact on heat stress responses, depending on the heat load and the disease severity. There is strong evidence that SkBF can be reduced in T1DM and T2DM induced by local heating or vasodilator compounds. During whole-body heat stress, impairments in heat loss have been shown in unfit T2DM sufferers and recreationally active T1DM patients if the level of heat production is high (i.e. 500 W). The independent effect of cardiovascular disease and hypertension is marginal during whole body heat stress, but secondary risk factors (i.e. very low fitness levels) are likely to be present in these populations.

Practical advice

- Based on the literature available, people with diabetes may be at risk during hot work.

- People with diabetes who have good glucose control should not be considered more at risk if they meet fitness standards and can acclimatize to the work.
- Cardiovascular disease and hypertension do not increase vulnerability to heat *per se*, but secondary risk factors such as very low fitness level increase susceptibility to heat stress.

The relative influence of individual characteristics

The relative influence of each physical characteristic on the T_c response and physical work capacity during heat stress is displayed in Figure 1. The T_c figure is most relevant from a health and safety perspective, as the International Standard states that average T_c should not exceed 38°C during a typical working day for a group of workers. The key factors for T_c control during heat stress are acclimation status, body mass, and fitness. The work capacity figures focus on how each factor influences work output in the heat, based on the assumption that work output is regulated by the HR, as has indeed been shown in the field (Brake and Bates, 2002; Mairiaux and Malchaire, 1985; Miller et al., 2011; Miller and Bates, 2007).

Conclusions

The present review has determined which individual characteristics are most relevant during physical work in the heat, in the context of health and work capacity. It should be noted that several other factors can independently influence thermophysiological responses to heat, such as dehydration (Cheuvront and Kenefick, 2014), some medications (Martin-Latry et al., 2007), and psychological stress (Boulant, 2010). The present review is written with the assumption that workers are hydrated, not on prescription medication, and are free of severe psychological distress. There is an urgent need to explore the interaction between multiple factors, and the time dependency for certain factors to take effect.

Abbreviations

A_D:mass: Skin surface area to mass ratio; BMI: Body mass index; E_{max}: Maximum evaporative potential; E_{req}: Required evaporation for heat balance; HSP72: Heat shock protein 72; ISO: International Standardisation Organisation; kPa: Water vapour pressure; NBC clothing: Nuclear, biological, and chemical protective clothing; ROC: Receiver operator characteristic; SkBF: Skin blood flow; T1DM and T2DM: Type 1 or 2 diabetes mellitus; T_c: Core temperature; $\dot{V}O_{2max}$: Maximal oxygen consumption; W: Watts; WBGT: Wet-bulb globe temperature; WHO: World Health Organisation

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Part 2: Individual Vulnerabilities – translating strain levels between different groups within the population

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Contents

Abstract

In this report an overview of available normative data on work capacity and relative strain based on workload, $\dot{V}O_{2max}$, and heart rate is provided.

The data are shown in relation to age groups, based on mean/median values for different age groups, but also the population percentile distribution is provided for $\dot{V}O_{2max}$ / workload in relation to age.

These relations can be used to consider the vulnerability models for different subgroups: gender, age and fitness.

Introduction

The majority of workload data and strain data used in the vulnerability models produced by Kjellstrom and co-workers is based on data for healthy, young to, at best middle aged, males. When considering different groupings, e.g. females or low or high fitness groups, these models may need adapting. In this section, the literature was searched for normative data on heart rate defined strain and on maximal work capacity ($\dot{V}O_{2max}$), to provide data for such adaptations. The report will initially look at population distribution of VO2 max as an indicator for work capacity and then look at ways to translate absolute workloads into relative cardio-vascular strain indicators for the work performed (light to very heavy).

NOTE: while the energy equivalent of a unit of oxygen consumed differs slightly based on the nutrient metabolised, a simple approximation will be used in this report that 1 litre of oxygen consumed per minute is equivalent to a metabolic energy generation of 350 Watt. Further it is assumed that all energy is produced aerobically (in contrast to anaerobic) given that the focus of the report is on longer term, sustained exercise.

Population distribution of maximal work capacity in relation to age.

Most models of work output, productivity in relation to heat stress simulate work at a certain metabolic rate. This metabolic is arbitrarily chosen based on an estimate of a typical workload.

The strain induced by this workload is however not only defined by the absolute workload value but also by the relative workload value in relation to an individual's maximal work capacity.

A classification of the strain of work in relation to age is provided by Andersen et al. (1978) in a WHO publication. Their data are based on values for the average maximal oxygen uptake in different age groups, and define strain level of work (light/moderate/heavy/very heavy) in terms of % of the $\dot{V}O_{2max}$. This will be discussed in more detail in the next section.

An issue here is that in order to consider vulnerability of a population, not only the average work capacity of the population is relevant, but also its distribution in the population. For the first, the average work capacity, an important factor to consider is age, as there is an abundance of data showing a reduction of work capacity with age, in part due to physiological changes of the body (so even when keeping up activity/training, $\dot{V}O_{2max}$ will reduce with age), and in part due to lifestyle changes (more sedentary, more obesity with age). For the second, the distribution of $\dot{V}O_{2max}$ values over population percentiles reflects work capacities. This distribution also changes with age.

NOTE: by definition, average work capacity would be based on a population mean, while in the percentile distribution, the middle point (50th percentile) would be based on the median. It seems however that these terms are used interchangeably in a big part of the literature.

Population distribution of maximal work capacity ($\dot{V}O_{2max}$)

Doing a literature search on this reveals that many sources, especially web based ones, provide tables with distributions indicating distributions of e.g. Poor, Fair, Good, Excellent or Superior fitness (Haywood, 2010) or Very weak, Weak, Lower regular, Upper regular, Good and Excellent (Nunes, 2004) and a few provide the percentiles, without the labelling shown above (ACSM 2018, Kaminsky et al 2015).

Unfortunately, many sources that provide such tables do not provide the original data, nor the references on which their tables are based. Others are not explicit about the testing method performed (real $\dot{V}O_{2max}$ test of submaximal test with extrapolation), the type of population used or about the number of data points/cases the tables are based on.

The main sources identified were from Astrand (1960), Golding at al. (1989), Heywood (1998 and 2010, with big differences between their tables between the two time points), Nunes et al. (2005) and finally the recent tables provided by ACSM (2018) based on the work by Kaminsky et al. (2015).

The data provided by these different sources with comments on their origin are shown in the tables in the appendix.

Based on the review of these literature sources, it is chosen to use the Kaminsky et al. (2015) data and categories based on percentiles. This data was presented in a 2015 paper and has been cited by ACSM in their most recent (2018) 'Guidelines for Exercise Testing and Prescription'. It is based on 7783 maximal exercise tests performed in eight US laboratories over a 13-month period. The authors conclude that these are the first cardiorespiratory fitness reference data using maximal tests compared to previous workload-derived estimations of $\dot{V}O_{2max}$ in the US population. The data include percentiles, i.e. not just arbitrary category descriptors such as poor, fair, good etc. (though in practice these may have been separated based on percentiles). It has not been possible to source all of the earlier original papers and reports. Therefore, in several cases exact details of participant numbers, protocols used and background for category labels (such as weak, good, excellent etc.) are unclear. Some papers (e.g. Andersen et al, 1978), present data as 'compiled from various sources', while these are not further detailed.

The data chosen as best representation is presented in Table 1:

Table 1, Kaminsky LA, Arena R, Myers J. Reference standards for cardiorespiratory fitness measured with cardiopulmonary exercise testing: data from the Fitness Registry and the Importance of Exercise National Database. Mayo Clinic Proceedings. 2015; 90 (11): 15. This table is based on 7783 persons $\dot{V}O_{2max}$ test. Data expressed in ml/kg/min.

MALES								
Percentiles of $\dot{V}O_{2max}$ distribution; units ml/kg/min								
Age	**5**	**10**	**25**	**50**	**75**	**90**	**95**	***n***
20-29	29.0	32.1	40.1	48.0	55.2	61.8	66.3	*513*
30-39	27.2	30.2	35.9	42.4	49.2	56.5	59.8	*963*
40-49	24.2	26.8	31.9	37.8	45.0	52.1	55.6	*1327*

50-59	20.9	22.8	27.1	32.6	39.7	45.6	50.7	*1078*
60-69	17.4	19.8	23.7	28.2	34.5	40.3	43.0	*593*
FEMALES								
Percentiles of $\dot{V}O_{2max}$ distribution; units ml/kg/min								
Age	**5**	**10**	**25**	**50**	**75**	**90**	**95**	***n***
20-29	21.7	23.9	30.5	37.6	44.7	51.3	56.0	*410*
30-39	19.0	20.9	25.3	30.2	36.1	41.4	45.8	*608*
40-49	17.0	18.8	22.1	26.7	32.4	38.4	41.7	*843*
50-59	16.0	17.3	19.9	23.4	27.6	32.0	35.9	*805*
60-69	13.4	14.6	17.2	20.0	23.8	27.0	29.4	*408*

This maximal work capacity expressed in ml/kg/min oxygen uptake, can be recalculated into an absolute maximal power output:

Energy consumption per unit of time (watts) = $\dot{V}O_{2max}$ (ml/kg/min) * body mass (kg) *350 (W/l/min)/1000 (ml/l).

While there of course is a wide spread of body masses, and the fitness level may interact with body mass (leaner people at high $\dot{V}O_{2max}$, more obese, heavier at lower $\dot{V}O_{2max}$ values), for simplicity the data from Table 1 are multiplied with the data for a reference man and women in Table 2, to produce Table 3.

NOTE: ISO 8996 has slightly different data for a reference male of 70kg and 175 cm and for the women of 60 kg, 170 cm.

Table 2 Behnke 1974; Gropper et al. 2005. Data for the reference man and women

	Reference man	Reference women
age	20-24	20-24
height	174	164
mass	70 kg	56.7 kg
Body fat %	15	27

Table 3, data from Kaminsky et al. (2005); ACSM (2018) converted to maximal work rate expressed in watts metabolic rate.

MALES								
Percentiles of maximal workload distribution; units watts								
Age	**5**	**10**	**25**	**50**	**75**	**90**	**95**	***n***
20-29	711	786	982	1176	1352	1514	1624	*513*
30-39	666	740	880	1039	1205	1384	1465	*963*
40-49	593	657	782	926	1103	1276	1362	*1327*
50-59	512	559	664	799	973	1117	1242	*1078*
60-69	426	485	581	691	845	987	1054	*593*

FEMALES								
Percentiles of maximal workload distribution; units watts								
Age	**5**	**10**	**25**	**50**	**75**	**90**	**95**	***n***
20-29	431	475	606	747	889	1020	1113	*410*
30-39	378	415	503	600	718	823	911	*608*
40-49	338	374	439	531	644	763	829	*843*
50-59	318	344	396	465	549	636	714	*805*
60-69	266	290	342	398	473	537	584	*408*

Relative Strain expressed in heart rate, energy expenditure and work strain in relation to age

A classification of the strain of work in relation to age is provided by Andersen et al. (1978) in a WHO publication. Their data are based on values for maximal oxygen uptake in different age groups. Next, they defined the classification of work in % of $\dot{V}O_{2max}$ ranges:

Table 4, Definition of relative workload from light to very heavy in terms of % $\dot{V}O_{2max}$. From WHO, Andersen et al, 1978.

Relative Workload Indicator	Related relative oxygen uptake
Light:	<25% $\dot{V}O_{2max}$
Moderate:	25-50% $\dot{V}O_{2max}$
Heavy:	50-75% $\dot{V}O_{2max}$
Very Heavy:	>75% $\dot{V}O_{2max}$

*NOTE: While in most literature this distribution of 25/50/75% $\dot{V}O_{2max}$ is used, One may argue that these percentages should be taken from the metabolic rate range available for extra work above resting. So, instead of e.g. taking the upper limit of 'light' as 25% $\dot{V}O_{2max}$, one would take the value of 'upper limit light'= resting $\dot{V}O_2$ + ($\dot{V}O_{2max}$ Resting $\dot{V}O_2$)*0.25*

While Andersen et al. (1978) in their WHO published book also provide distributions of maximal work capacity with age, we chose instead to use the Kaminsky data for this as discussed in section 1 (the result when using the original Andersen et al. (1978) data is shown in the appendix). The reasoning behind this is that the Andersen et al. (1978) reference does not specify the sources for the data they show in their tables (the refer to 'compiled from various sources'. Considering the authors background, it is most likely to be based on data from the work from Astrand and Rodahl (see appendix), which is considered not to be a good representation of the current population average.

Using the Kaminsky et al. distribution (Table 3) and their data on distribution of average VO2 max values over age, this can be converted to the following figures. If the workload is known, i.e. the related metabolic rate, the strain level can be then defined. For the 50th percentiles fitness level in each age group this is presented in the figures below, followed by 25th and 75th percentiles. Other percentiles can be easily calculated from the data in Table 3.

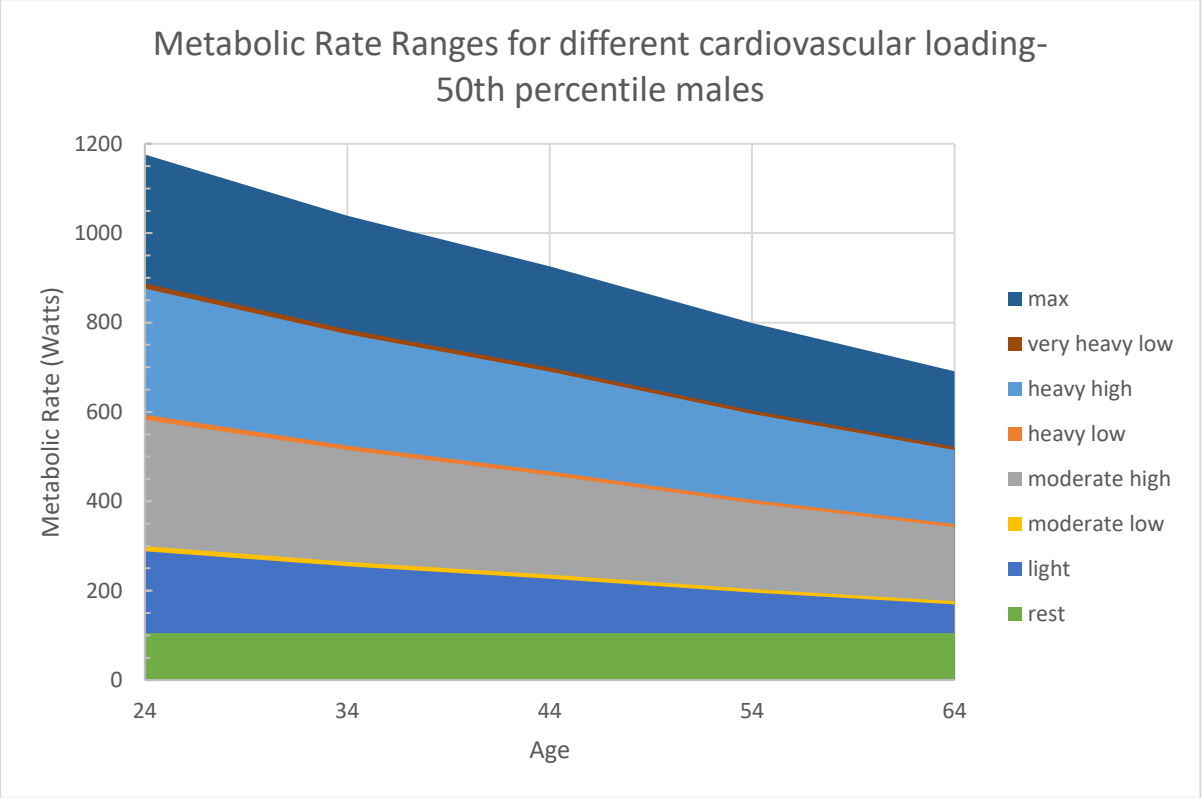

Figure 1, 50th percentile Male Work Capacity and Relative Strain descriptors based on the relative strain definition by WHO Andersen et al. (1978), combined with more up to date data on maximal workload distribution with age. Data based on 50th percentile for each age group defined by Kaminsky et al. (2005).

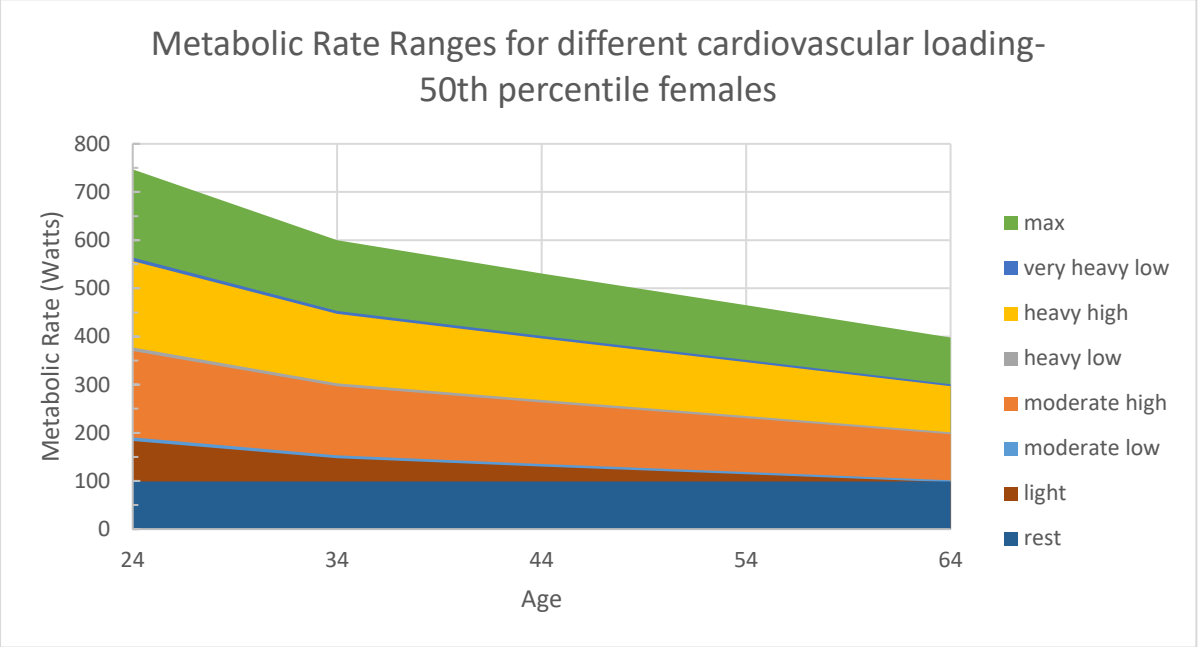

Figure 2, 50th percentile Female Work Capacity and Relative Strain descriptors based on the relative strain definition by WHO Andersen et al. (1978), combined with more up to date data on maximal workload distribution with age. Data based on 50th percentile for each age group defined by Kaminsky et al. (2005).

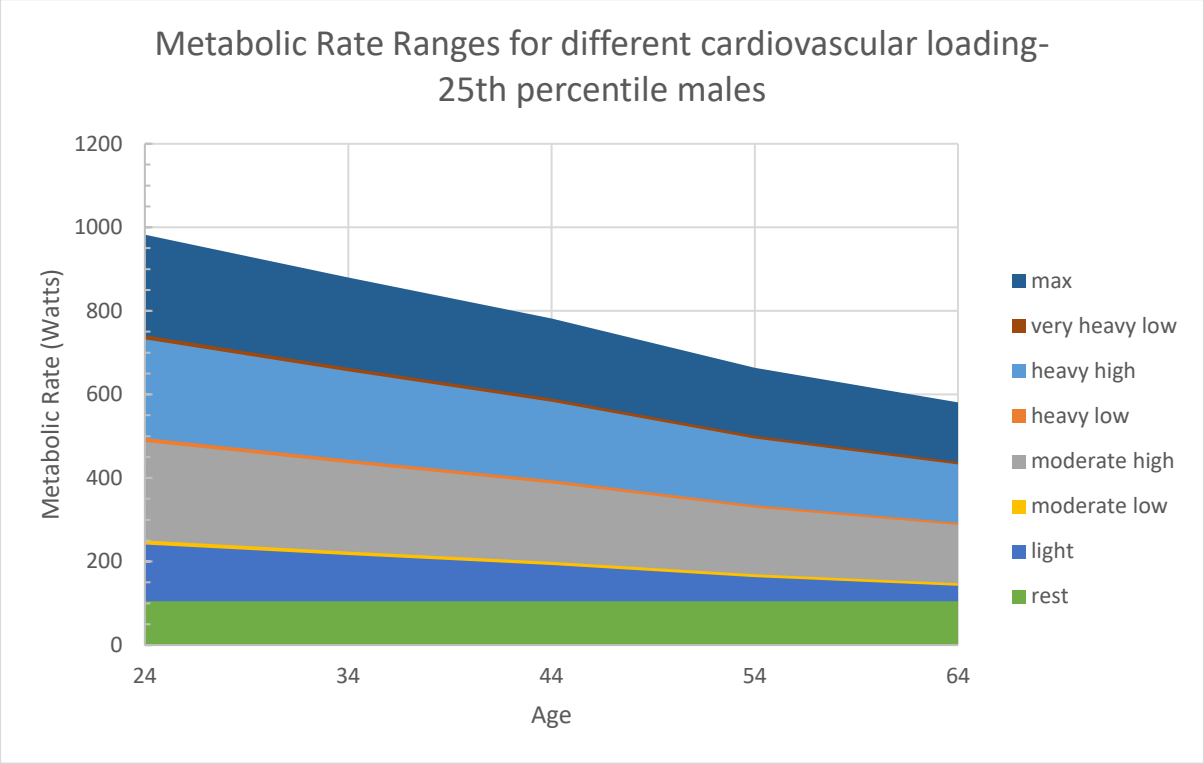

Figure 3, 25th percentile Male Work Capacity and Relative Strain descriptors based on the relative strain definition by WHO Andersen et al. (1978), combined with more up to date data on maximal workload distribution with age. Data based on 50th percentile for each age group defined by Kaminsky et al. (2005).

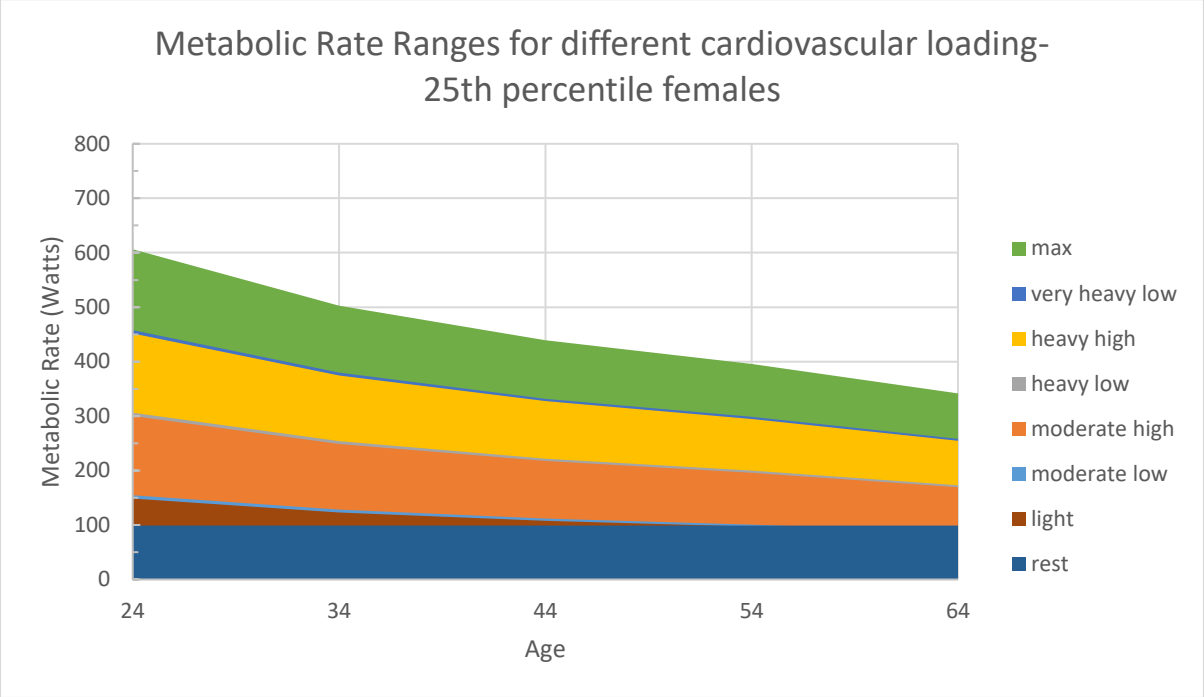

Figure 4 25th percentile Female Work Capacity and Relative Strain descriptors based on the relative strain definition by WHO Andersen et al. (1978), combined with more up to date data on maximal workload distribution with age. Data based on 50th percentile for each age group defined by Kaminsky et al. (2005).

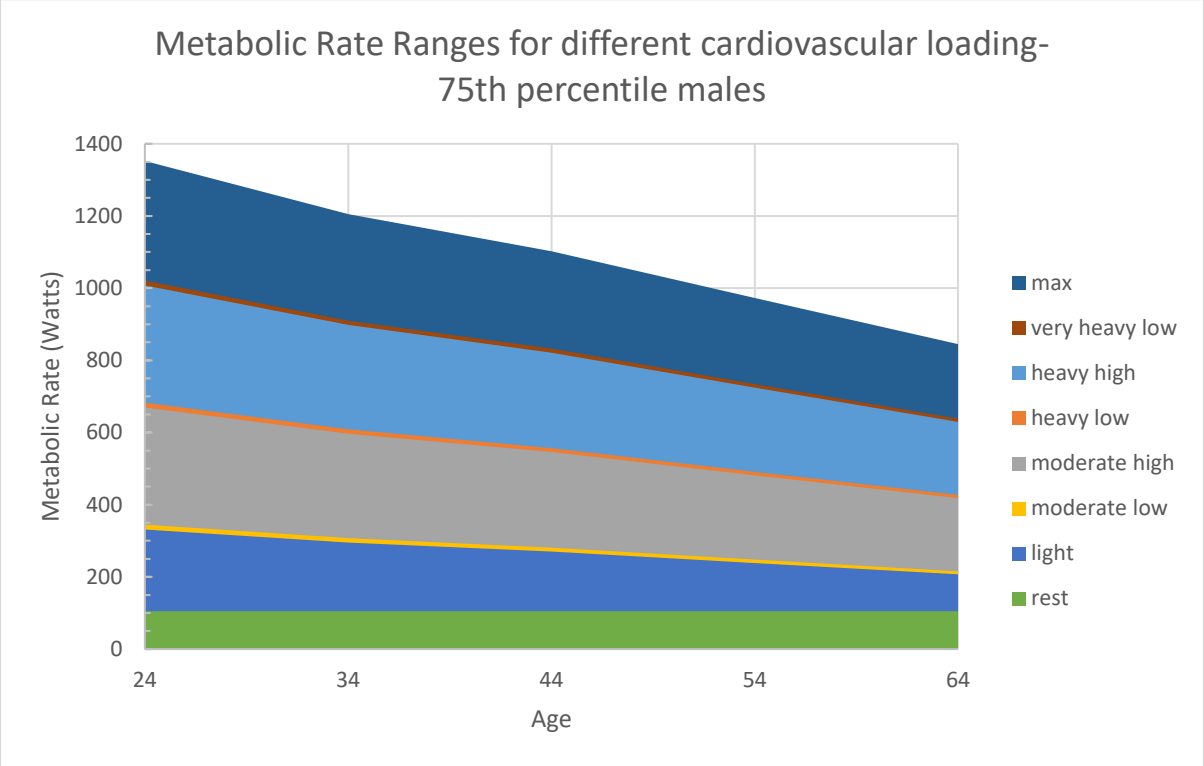

Figure 5, 75th percentile Male Work Capacity and Relative Strain descriptors based on the relative strain definition by WHO Andersen et al. (1978), combined with more up to date data on maximal workload distribution with age. Data based on 50th percentile for each age group defined by Kaminsky et al. (2005).

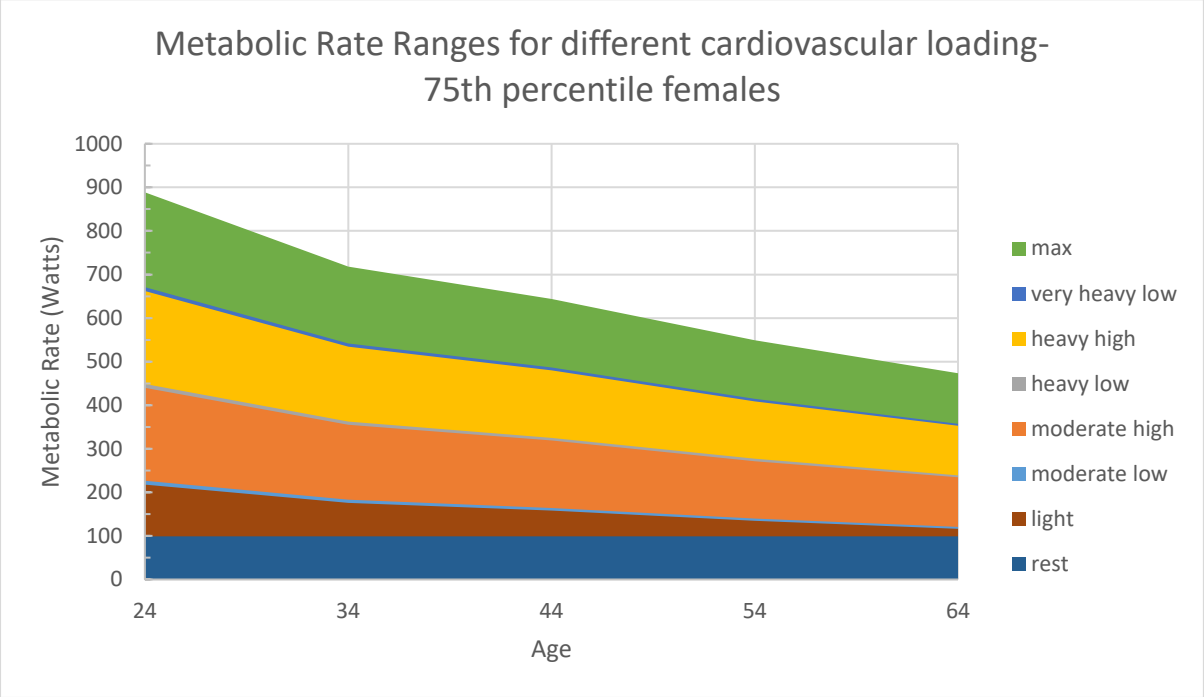

Figure 6, 75th percentile Female Work Capacity and Relative Strain descriptors based on the relative strain definition by WHO Andersen et al. (1978), combined with more up to date data on maximal workload distribution with age. Data based on 50th percentile for each age group defined by Kaminsky et al. (2005).

NOTE: As shown in Figure 2*, the 'light' category disappears for the 60+ year old females. The definition of this category (<25% $\dot{V}O_{2max}$) may need to be reconsidered with a reduced resting value, or alternatively, as suggested in the previous note, the ranges should be defined as % of the ($\dot{V}O_{2max}$ - $\dot{V}O_2$ rest) range.*

Recalculating these metabolic rate into oxygen uptakes, and assuming a typical body weight of around 70 kg, the $\dot{V}O_{2max}$ for the young males 50th percentile is around 3.36 l/min, or 48.0 ml/kg/min. For the females this would be 2.13 l/min, or 37.6 ml/min/kg (56.7kg). *[if using the original Andersen et al. data (1978) these values would be around 3.32 l/min, or 47.4 ml/min/kg. For the females this would be 1.86 l/min, or 32.8 ml/min/kg]*.

These strain levels are based on the estimated average fitness levels for each age group. These would need to be considered in relation to the distribution of $\dot{V}O_{2max}$ values within the population given in section one, and the same distributions of load ratings can be produced for each percentile of fitness levels present in the overall population.

Heart rate as strain indicator.

Alternatively, and probably more easy to generalise, is to define the strain levels based on cardiovascular strain. The person's heart rate is a good indicator for this, representing a combined strain index that includes both metabolic and heat related strain. The metabolic

strain of the work performed is translated in the heart rate required to deliver the oxygen and nutrients to the working muscles. Ideally cardiac output (CAout=heart rate * stroke volume) would be used, but that is a difficult measure in the field.

In the translation of the metabolic data above into cardiac strain, a similar approach as in table 1 can be used. I.e. expressing the heart rate as % of the range between rest and maximum. The metabolic work performed (metabolic rate-resting metabolic rate) is directly linked to increases in circulatory flow and heart rate.

The heart rate range available for work depends on age. While resting heart rate is only minimally affected by age for an average fit person, the maximal heart rate is strongly affected, with reductions in maximal heart rate defined as:

HR_{max}=220-age

Or

HR_{max}=210-.65*age

Using this function, and resting HR the following relations are obtained, which are virtually identical for males and females. In that contexts it should be noted that while cardiovascular strain for a certain heart rate is similar, metabolic rate will be very different, depending on age, gender and percentile of $\dot{V}O_{2max}$ distribution.

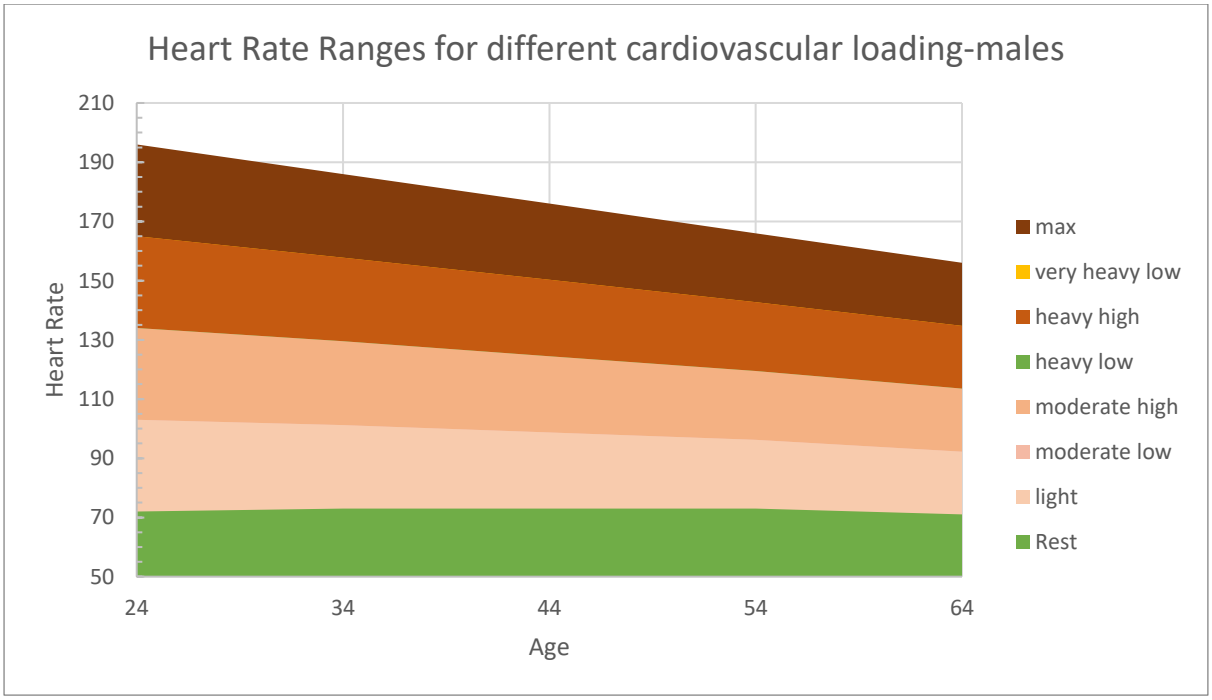

Figure 7, Male relative workload categories based on heart rates in relation to age.

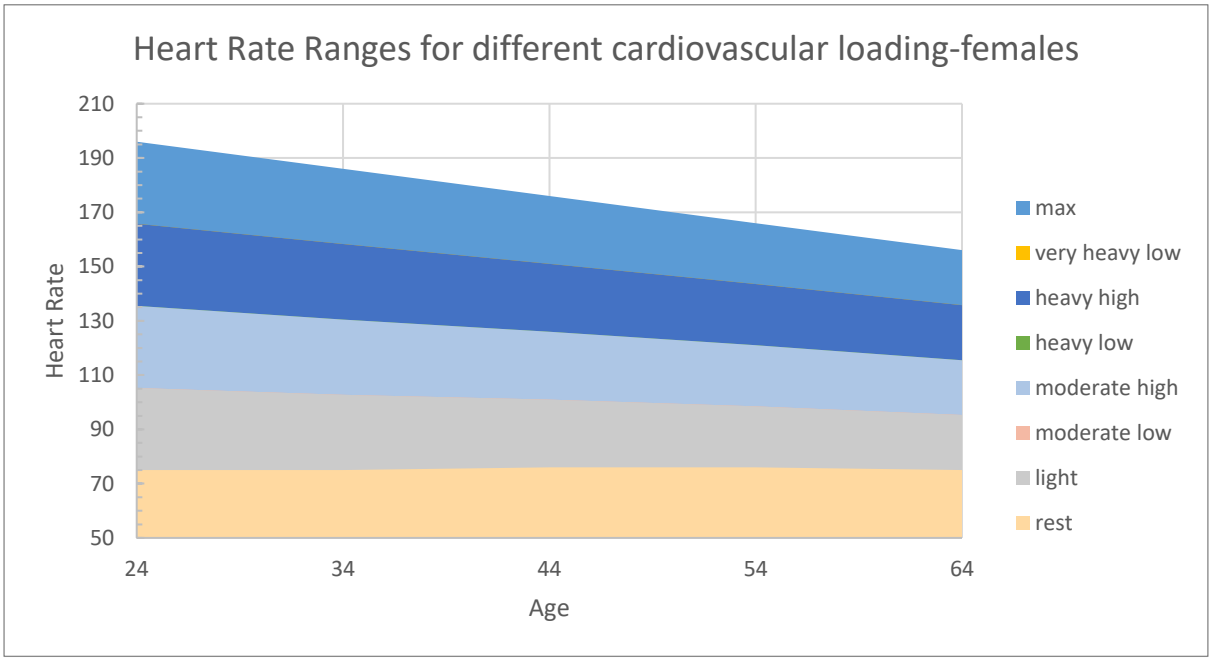

Figure 8, Female relative workload categories based on heart rates in relation to age.

These relations allow us to translate strain between age groups and calculate the heart rates for equivalent strain. In the graphs below this is presented in two ways. In the first two, and in the second column of

Table 5, the HR of older people (y axes) is shown in relation to that of the youngest group (20-29, x-axis) with equations in the table.

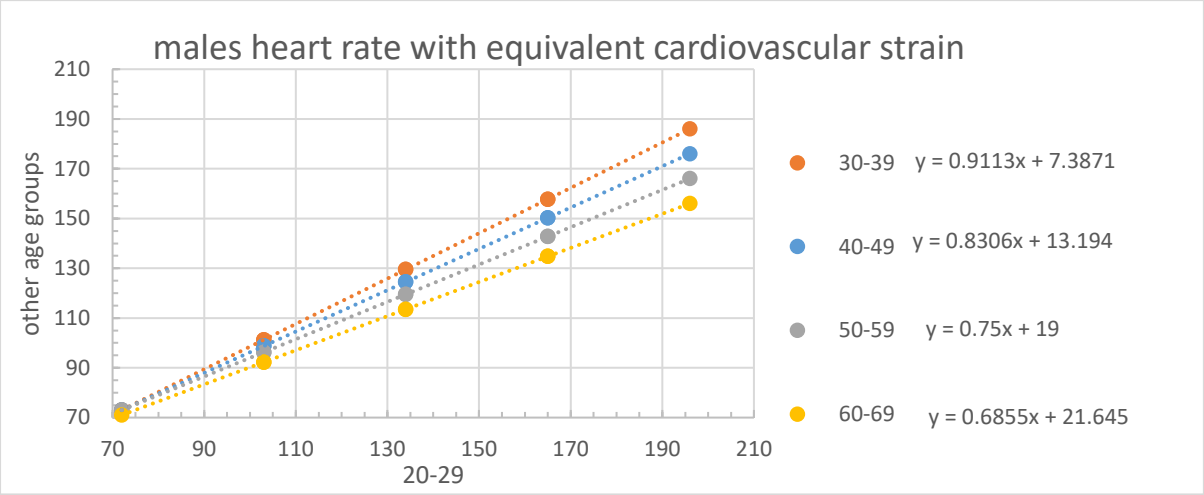

Figure 9, HR of older people (y axes) is shown in relation to that of the youngest group (20-29, x-axis) for Males

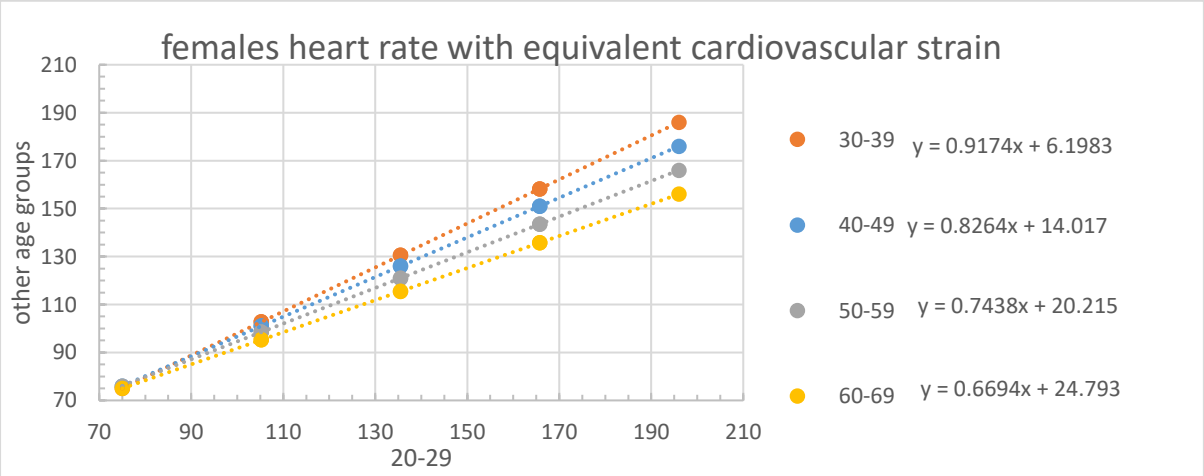

Figure 10, HR of older people (y axes) is shown in relation to that of the youngest group (20-29, x-axis) for females.

In the third column of

Table 5 and the next two graphs, the reverse is shown: the HR of younger people (y axes) is shown in relation to that of the older groups (x-axis).

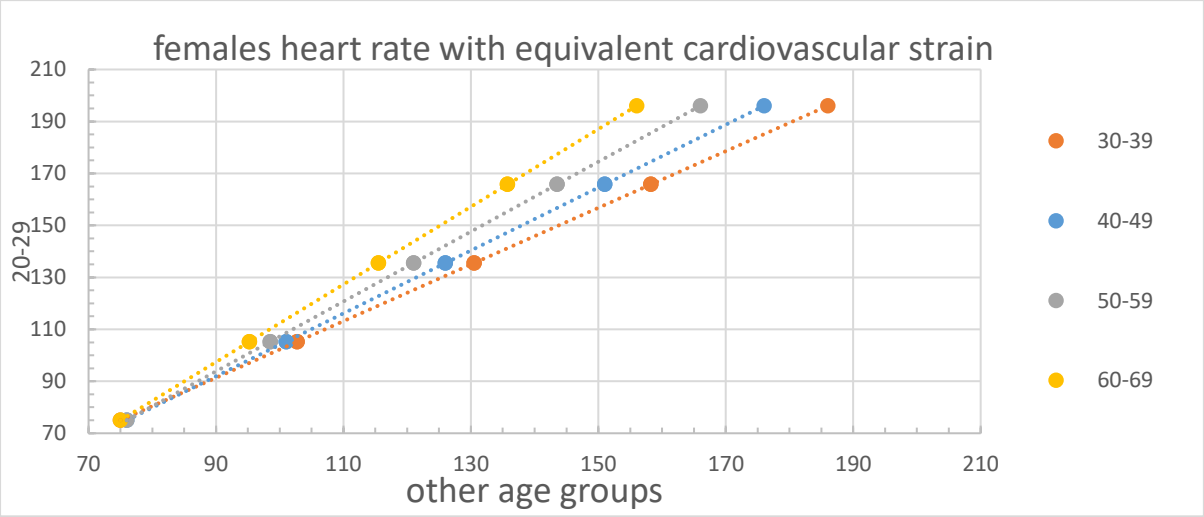

Figure 11, the HR of younger people (y axes) is shown in relation to that of the older groups (x-axis) for Males.

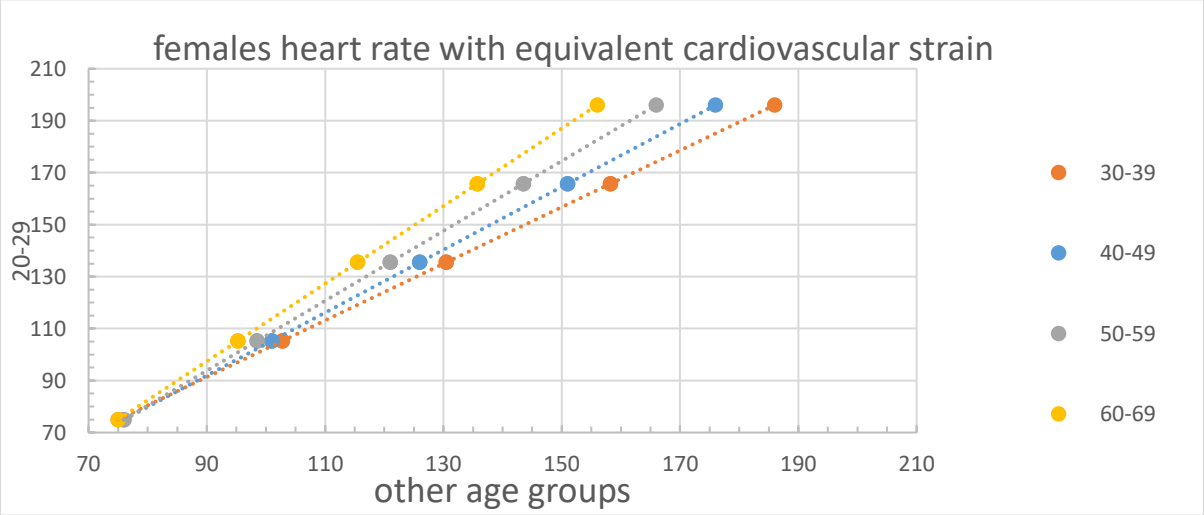

Figure 12, the HR of younger people (y axes) is shown in relation to that of the older groups (x-axis) Females.

Thus, to translate the strain level heart rate from an older person to the equivalent heart rate strain level of a younger person, or vice-versa the following equations can be used:

E.g., If a 64 year old female has a HR of 150 bmp, this represents the same strain level as if a 24 year old has a heart rate of 1.494*100-37=187 bpm.

Table 5, Equations for the conversion of equivalent cardiovascular strain heart rate values between different age groups. In column 2 the equations convert the HR of a young person into the equivalent strain HR of an older person (lower). In column 3 the equations convert the HR of an older person into the equivalent strain HR of a younger person (higher). This conversion incorporates the effect of reductions in maximal heart rate with age.

Males, conversion of equivalent strain heart rate:	X=equivalent strain heart rate young person; y =equivalent strain heart rate older person	X=equivalent strain heart rate old person; y =equivalent strain heart rate young person
30-39	y = 0.9113x + 7.3871	y = 1.0973x - 8.1062
40-49	y = 0.8306x + 13.194	y = 1.2039x - 15.883
50-59	y = 0.75x + 19	y = 1.3333x - 25.333
60-69	y = 0.6855x + 21.645	y = 1.4588x - 31.576
Females, conversion of equivalent strain heart rate:	X=equivalent strain heart rate young person; y =equivalent strain heart rate older person	X=equivalent strain heart rate old person; y =equivalent strain heart rate young person
30-39	y = 0.9113x + 7.3871	y = 1.0901x - 6.7568
40-49	y = 0.8306x + 13.194	y = 1.21x - 16.96
50-59	y = 0.75x + 19	y = 1.3444x - 27.178
60-69	y = 0.6855x + 21.645	Y = 1.4938x - 37.037

Similarly, these data can be used to translate equivalent strain heart rate values between males and females.

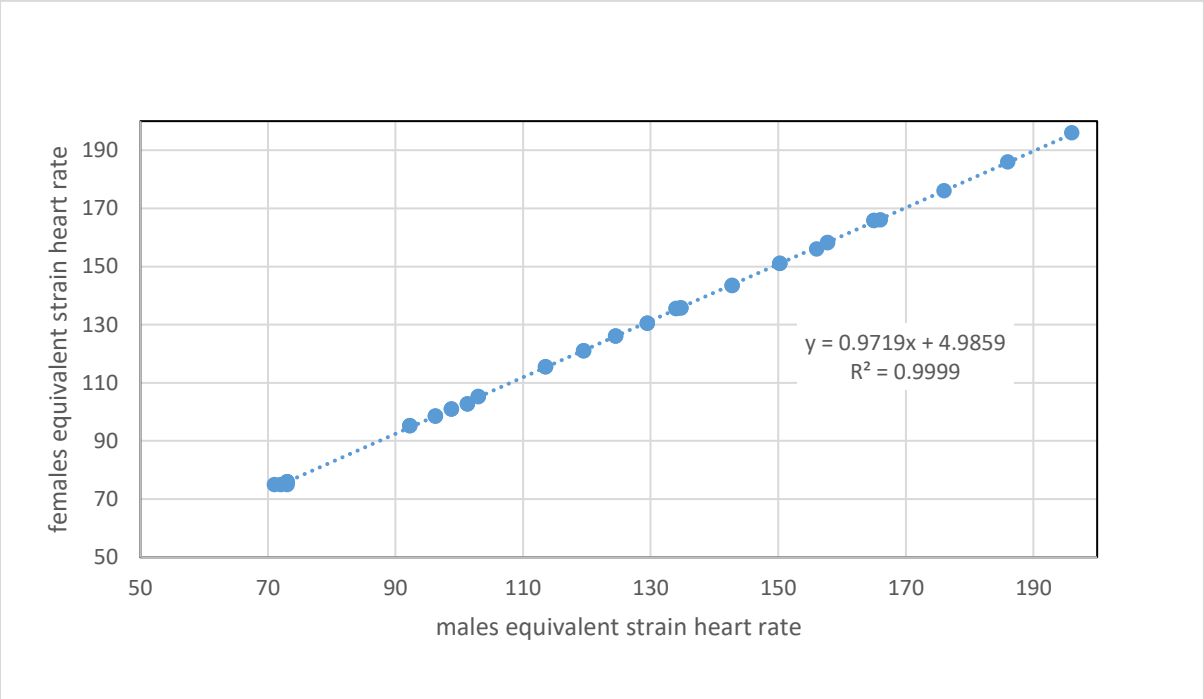

Figure 13

To calculate the equivalent strain heart rate for a female based on that of a male:

$y = 0.9719x + 4.9859$; $R^2 = 0.9999$

and, to calculate the equivalent strain heart rate for a male based on that of a female:

$y = 1.0287x - 5.113$; $R^2 = 0.9999$

e.g. if a female has a heart rate of 150, this is equivalent in strain to a male having a heart rate of 1.0287 * 150 – 5.1 = 149.

This correction is quite small, and possibly negligible.

Based on the above, one can combine the effect of age and gender. Translating e.g. the strain HR of a 64 year old female to that of a 24 year old male takes two steps:

1: If a 64 year old female has a HR of 150 bmp, this represents the same strain level as if a 24 year old female has a heart rate of 1.494*100-37=187 bpm.

2: This heart rate of 187 in a young female is equivalent to 1.0287* 187 – 5.1=187 in a same age male..

Summary

In this report an overview of available normative data on work capacity and relative strain based on workload, $\dot{V}O_{2max}$, and heart rate is provided.

The data are shown in relation to age groups, based on mean/median values for different age groups, but also the population percentile distribution is provided for $\dot{V}O_{2max}$ / workload in relation to age.

These relations can be used to consider the vulnerability models for different subgroups: gender, age, fitness.

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ACSM's Guidelines for Exercise Testing and Prescription (2018). Adapted with permission from Kaminsky LA, Arena R, Myers J. Reference standards for cardiorespiratory fitness measured with cardiopulmonary exercise testing: data from the Fitness Registry and the Importance of Exercise National Database.

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Gropper SS, Smith JL, Groff JL. Advanced Nutrition and Human Metabolism. fourth ed: Thomson Wadsworth; 2005.

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Heywood, V. (2010) The Physical Fitness Specialist Manual, The Cooper Institute for Aerobics Research, Dallas TX, revised 2005. In: HEYWOOD, V (2010) Advanced Fitness Assessment and Exercise Prescription, Sixth Edition, Champaign, IL: Human Kinetics.

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Nunes et al. (2004) in Nunes, R. A. M.; Pontes, G. F. R.; Dantas, P. M. S.; Fernandes Filho, J. Referencial table of cardiopulmonary fitness. Fitness & Performance Journal, v. 4, n. 1, p. 27 - 33, 2005

Appendix 1: Normative data on population distribution of maximal work capacity.

Table 6, $\dot{V}O_{2max}$ norms adapted from Astrand: ACTA Physiol Scand. 49 (Suppl): 169, 1960. Main criticisms in other papers is that young men and women were highly trained.

				MALES			
Age	**Low**	**Fair**	**Avg.**	**Good**	**High**	**Athletic**	**Olympic**
20-29	<38	39-43	44-51	52-56	57-62	63-69	70+
30-39	<34	35-39	40-47	48-51	52-57	58-64	65+
40-49	<30	31-35	36-43	44-47	48-53	54-60	61+
50-59	<25	26-31	32-39	40-43	44-48	49-55	56+
60-65	<21	22-26	27-35	36-39	40-44	45-49	50+
				FEMALES			
Age	**Low**	**Fair**	**Avg.**	**Good**	**High**	**Athletic**	**Olympic**
20-29	<28	29-34	35-43	44-48	49-53	54-59	60+
30-39	<27	28-33	34-41	42-47	48-52	53-58	59+
40-49	<25	26-31	32-40	41-45	46-50	51-56	57+
50-65	<21	22-28	29-36	37-41	42-45	46-49	50+

Table 7, Y's Way to Physical Fitness (3rd edition) by Golding, Myers and Sinning (1989). Cited in Morrow JR, Jackson AW, Disch JG and Mood DP (1995) Measurement and Evaluation in Human Performance; Human Kinetics, Champlain, IL. Data is based on sub-maximal tests.

				MALES			
Age	**Very poor**	**Poor**	**Below average**	**Average**	**Above average**	**Good**	**Excellent**
18 - 25	20 - 29	31 - 35	38 - 41	43 - 46	47 - 51	53 - 59	63 - 80
26 - 35	20 - 28	31 - 34	35 - 39	40 - 42	44 - 47	50 - 54	58 - 70
36 - 45	19 - 25	27 - 30	32 - 34	35 - 38	40 - 42	44 - 49	53 - 77
46 - 55	18 - 23	26 - 28	29 - 31	32 - 35	35 - 38	40 - 43	47 - 60
56 - 65	16 - 21	22 - 25	26 - 29	30 - 31	33 - 35	37 - 39	43 - 58
> 65	15 - 18	20 - 21	22 - 25	25 - 28	29 - 32	33 - 36	38 - 50
				FEMALES			
Age	**Very poor**	**Poor**	**Below average**	**Average**	**Above average**	**Good**	**Excellent**
18 - 25	18 - 26	29 - 32	34 - 37	39 - 41	42 - 46	48 - 54	58 - 71
26 - 35	20 - 25	26 - 30	31 - 34	35 - 38	40 - 43	46 - 51	54 - 69
36 - 45	18 - 21	23 - 26	28 - 30	31 - 33	34 - 37	39 - 44	46 - 66
46 - 55	16 - 19	21 - 24	25 - 27	28 - 30	31 - 33	35 - 39	42 - 64

56 - 65	14 - 17	19 - 21	22 - 24	25 - 27	28 - 31	32 - 36	38 - 57
> 65	14 - 16	17 - 18	20 - 22	22 - 24	25 - 27	28 - 31	33 - 51

Table 8, HEYWOOD, V. (1998) The Physical Fitness Specialist Certification Manual, The Cooper Institute for Aerobics Research, Dallas TX, revised 1997. In: HEYWOOD, V (1998) Advance Fitness Assessment & Exercise Prescription, 3rd Ed. Leeds: Human Kinetics. p. 48. Test type unclear. Other papers suggest the cooper clinic data is predicted from sub-maximal Balke tests.

				MALES		
Age	**Very Poor**	**Poor**	**Fair**	**Good**	**Excellent**	**Superior**
20-29	<33.0	33.0 - 36.4	36.5 - 42.4	42.5 - 46.4	46.5 - 52.4	>52.4
30-39	<31.5	31.5 - 35.4	35.5 - 40.9	41.0 - 44.9	45.0 - 49.4	>49.4
40-49	<30.2	30.2 - 33.5	33.6 - 38.9	39.0 - 43.7	43.8 - 48.0	>48.0
50-59	<26.1	26.1 - 30.9	31.0 - 35.7	35.8 - 40.9	41.0 - 45.3	>45.3
60+	<20.5	20.5 - 26.0	26.1 - 32.2	32.3 - 36.4	36.5 - 44.2	>44.2
				FEMALES		
Age	**Very Poor**	**Poor**	**Fair**	**Good**	**Excellent**	**Superior**
20-29	<23.6	23.6 - 28.9	29.0 - 32.9	33.0 - 36.9	37.0 - 41.0	>41.0
30-39	<22.8	22.8 - 26.9	27.0 - 31.4	31.5 - 35.6	35.7 - 40.0	>40.0
40-49	<21.0	21.0 - 24.4	24.5 - 28.9	29.0 - 32.8	32.9 - 36.9	>36.9
50-59	<20.2	20.2 - 22.7	22.8 - 26.9	27.0 - 31.4	31.5 - 35.7	>35.7
60+	<17.5	17.5 - 20.1	20.2 - 24.4	24.5 - 30.2	30.3 - 31.4	>31.4

Table 9, HEYWOOD, V. (2010) The Physical Fitness Specialist Manual, The Cooper Institute for Aerobics Research, Dallas TX, revised 2005. In: HEYWOOD, V (2010) Advanced Fitness Assessment and Exercise Prescription, Sixth Edition, Champaign, IL: Human Kinetics.

			MALES		
Age	**Poor**	**Fair**	**Good**	**Excellent**	**Superior**
20 - 29	<42	42 - 45	46 - 50	51 - 55	>56
30 - 39	<40	41 - 43	44 - 47	48 - 53	>54
40 - 49	<37	38 - 41	42 - 45	46 - 52	>53
50 - 59	<34	35 - 37	38 - 42	43 - 49	>50
60 - 69	<30	31 - 34	35 - 38	39 - 45	>46
70 - 79	<27	28 - 30	31 - 35	36 - 41	>42
			FEMALES		
Age	**Poor**	**Fair**	**Good**	**Excellent**	**Superior**
20 - 29	<35	36 - 39	40 - 43	44 - 49	>50
30 - 39	<33	34 - 36	37 - 40	41 - 45	>46
40 - 49	<31	32 - 34	35 - 38	39 - 44	>45
50 - 59	<28	29 -30	31 - 34	35 - 39	>40
60 - 69	<25	26 - 28	29 - 31	32 - 36	>37
70 - 79	<23	24 - 26	27 - 29	30 - 36	>37

Table 10, Nunes et al. (2004) in Nunes, R. A. M.; Pontes, G. F. R.; Dantas, P. M. S.; Fernandes Filho, J. Reference table of cardiopulmonary fitness. Fitness & Performance Journal, v. 4, n. 1, p. 27 - 33, 2005. Brazilian data published in Brazilian journal, not great english, difficult to be sure maximal tests performed. Data seem lower than most other, good is considered top 10%.

				MALES			
Age	**Very weak**	**Weak**	**Lower regular**	**Upper regular**	**Good**	**Excellent**	**n**
Percentile	**10%**	**25%**	**50%**	**75%**	**90%**	**95%**	
20-29	<25	25-30	31-37	38-43	44-49	>49	902
30-39	<23	23-28	29-34	35-40	41-45	>45	1132
40-49	<20	20-25	26-30	31-36	37-41	>41	691
50-59	<18	18-22	23-26	27-31	32-35	>35	261
60-69	<17	17-21	22-25	26-29	30-33	>33	116
>70	<16	16-20	21-24	25-28	29-32	>32	45
				FEMALES			
Age	**Very weak**	**Weak**	**Lower regular**	**Upper regular**	**Good**	**Excellent**	**n**
Percentile	**10%**	**25%**	**50%**	**75%**	**90%**	**95%**	
20-29	<24	24-28	29-32	33-36	37-40	>40	1315
30-39	<22	22-26	27-30	31-34	35-38	>38	1928
40-49	<19	19-23	24-27	28-32	33-36	>36	868
50-59	<16	16-20	21-24	25-28	29-33	>33	407
60-69	<15	15-19	20-22	23-25	26-28	>28	101
>70	<15	15-18	19-21	22-24	25-26	>26	21

Table 11, ACSM's Guidelines for Exercise Testing and Prescription (2018). Adapted with permission from Kaminsky LA, Arena R, Myers J. Reference standards for cardiorespiratory fitness measured with cardiopulmonary exercise testing: data from the Fitness Registry and the Importance of Exercise National Database. Mayo Clin Proc. 2015; 90 (11): 1515-23.

				MALES			
Age	**Very poor**	**Poor**	**Fair**	**Good**	**Excellent**	**Superior**	**n**
Percentile	**5-15%**	**20-35%**	**40-55%**	**60-75%**	**80-90%**	**95%**	
20-29	29.0 - 35.4	38.1 - 43.5	44.9 - 49.0	50.2 - 55.2	57.1 - 61.8	66.3	513
30-39	27.2 - 32.7	34.1 - 38.5	39.6 - 43.8	45.2 - 49.2	51.6 - 56.5	59.8	963
40-49	24.2 - 29.0	30.5 - 34.6	35.7 - 38.9	40.3 - 45.0	46.7 - 52.1	55.6	1327
50-59	20.9 - 24.4	26.1 - 29.5	30.7 - 33.8	35.1 - 39.7	41.2 - 45.6	50.7	1078
60-69	17.4 - 21.2	22.4 - 25.7	26.6 - 29.1	30.5 - 34.5	36.1 - 40.3	43	593
				FEMALES			
Age	**Very poor**	**Poor**	**Fair**	**Good**	**Excellent**	**Superior**	**n**
Percentile	**5-15%**	**20-35%**	**40-55%**	**60-75%**	**80-90%**	**95%**	
20-29	21.7 - 26.2	28.6 - 33.6	34.6 - 38.9	40.6 - 44.7	46.5 - 51.3	56.0	410
30-39	19.0 - 22.5	24.1 - 27.4	28.2 - 31.2	32.2 - 36.1	37.5 - 41.4	45.8	608
40-49	17.0 - 20.0	21.3 - 24.1	24.9 - 27.7	28.7 - 32.4	34.0 - 38.4	41.7	843
50-59	16.0 - 18.3	19.1 - 21.2	21.8 - 24.4	25.2 - 27.6	28.6 - 32.0	35.9	805
60-69	13.4 - 15.6	16.5 - 18.4	18.9 - 20.5	21.2 - 23.8	24.6 - 27.0	29.4	408

Table 12, Kaminsky LA, Arena R, Myers J. Reference standards for cardiorespiratory fitness measured with cardiopulmonary exercise testing: data from the Fitness Registry and the Importance of Exercise National Database. Mayo Clinic Proceedings. 2015; 90 (11): 15

				MALES				
Age	**5**	**10**	**25**	**50**	**75**	**90**	**95**	**n**
20-29	29.0	32.1	40.1	48.0	55.2	61.8	66.3	513
30-39	27.2	30.2	35.9	42.4	49.2	56.5	59.8	963
40-49	24.2	26.8	31.9	37.8	45.0	52.1	55.6	1327
50-59	20.9	22.8	27.1	32.6	39.7	45.6	50.7	1078
60-69	17.4	19.8	23.7	28.2	34.5	40.3	43.0	593
				FEMALES				
Percentile	**5**	**10**	**25**	**50**	**75**	**90**	**95**	**n**
20-29	21.7	23.9	30.5	37.6	44.7	51.3	56.0	410
30-39	19.0	20.9	25.3	30.2	36.1	41.4	45.8	608
40-49	17.0	18.8	22.1	26.7	32.4	38.4	41.7	843
50-59	16.0	17.3	19.9	23.4	27.6	32.0	35.9	805
60-69	13.4	14.6	17.2	20.0	23.8	27.0	29.4	408

Appendix 2: Work capacity distribution based on Andersen et al. (1978) data.

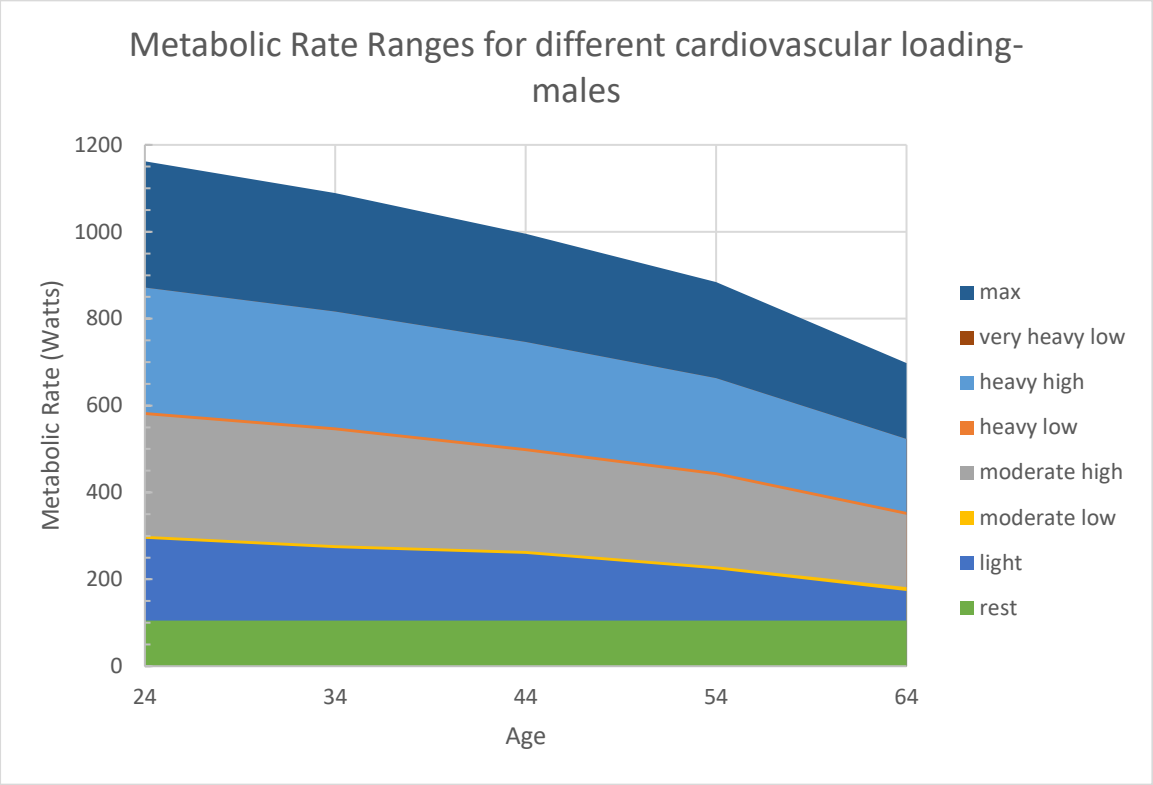

Figure 14, Data from Andersen et al. (1978).

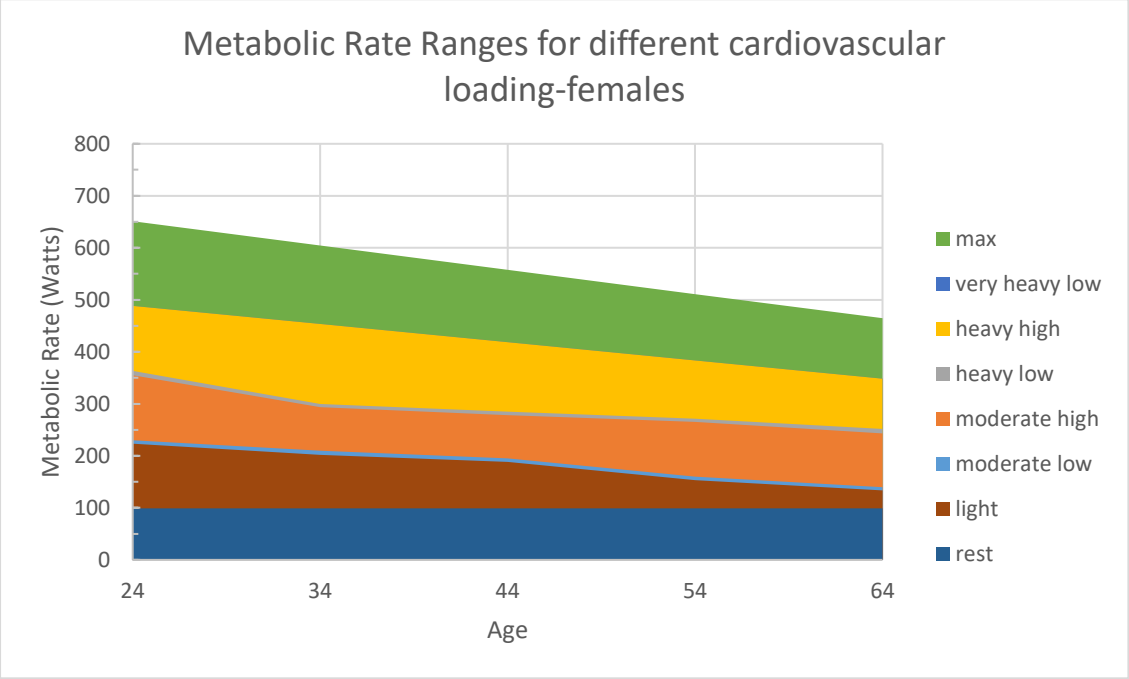

Figure 15, Data adapted from Andersen et al. (1978). The inconsistent shape of the curves indicates a possible error in the original calculations by Andersen et al. (1978).

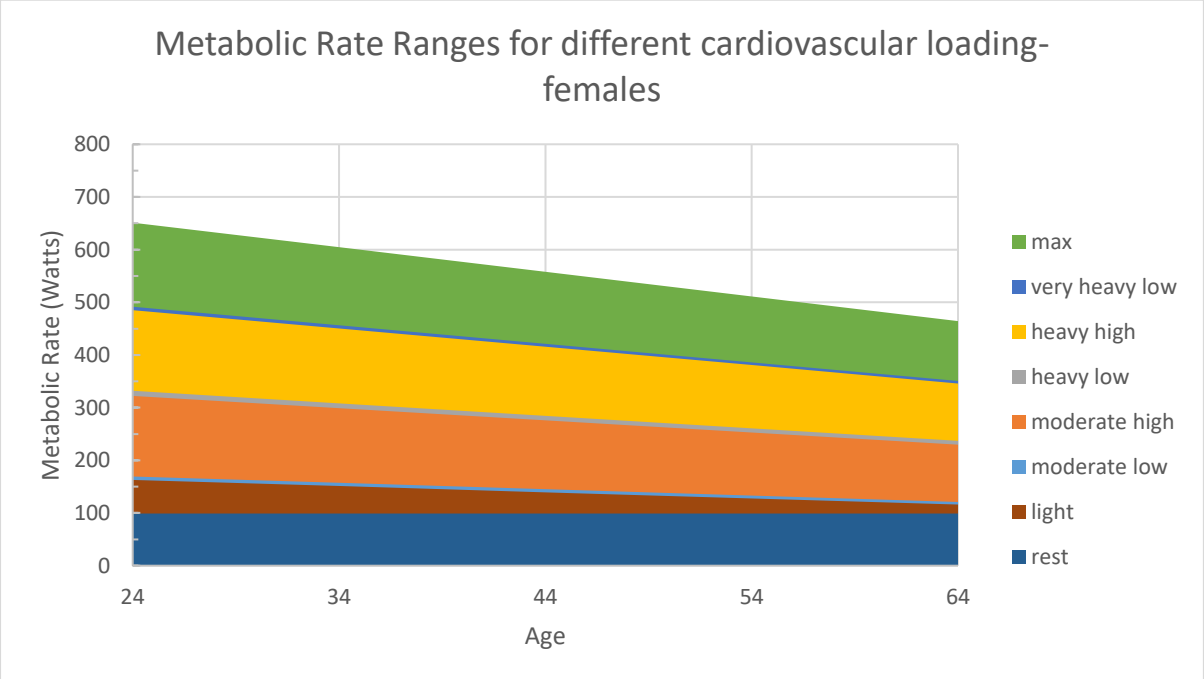

Figure 16, Data adapted from Andersen et al. (1978). Data corrected based on relations described by Andersen in their paper.

Part 3 Individual vulnerability modelling using thermophysiological models.

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This section provides information on the incorporation of individual factors, as described in the literature review for Heat-Shield, D2.1, Part 1, into thermophysiological models that can be used in the modelling of vulnerability of different population groupings as well as in the development of the thermophysiological control model for the human simulator.

This material feeds into the work for task 3.2.

The section is building on research performed by Havenith (2001) and the text relates in the main to relevant sections summarized recently by Fiala and Havenith, 2016:

Fiala D, Havenith G. Modelling Human Heat Transfer and Temperature Regulation. In: The Mechanobiology and Mechanophysiology of Military-Related Injuries. Eds. A. Gefen & Y. Epstein, Springer Series "Studies in Mechanobiology, Tissue Engineering and Biomaterials", 2015, in press. DOI 10.1007/8415_2015_183; ISBN 978-3-319-33012-9.

Note: for the actual equations listed in this section, please refer to the reference, to ensure no errors have been introduced in this summary.

Modelling Human Heat Transfer and Temperature Regulation

Authors: Dusan Fiala and George Havenith

1 Modelling the Passive System

1.1 Body Construction

The passive system is modelled as a composite of cylindrical and spherical (head) body elements built of concentric tissue layers (section A-A″ in Fig. 1) with skin represented as inner cutaneous layer (incorporating the cutaneous plexus) and outer

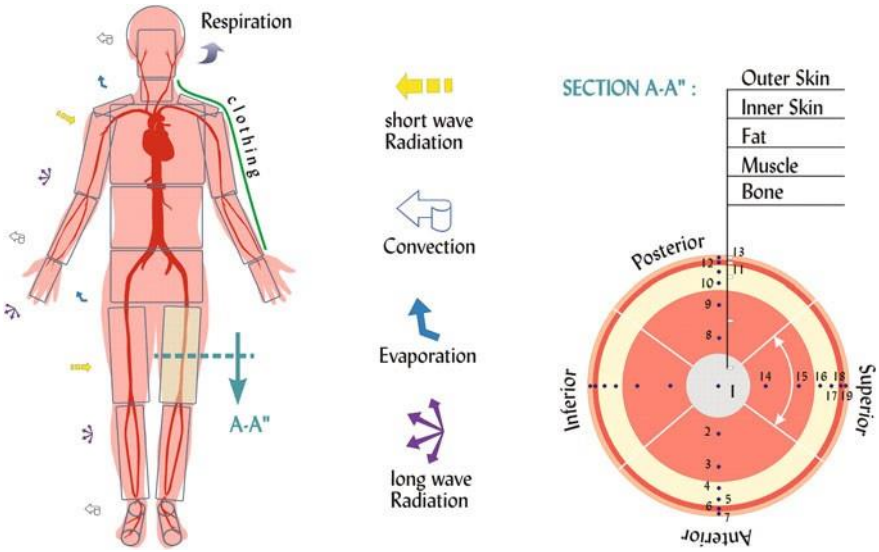

Fig. 1 Schematic diagram of the passive system model including body subdivisions, components of the environmental heat exchange, and a crosssection through the upper leg (*right*)

skin. The latter contains sweat glands but no thermally significant blood vessels [17, 24]. As indicated in Fig. 1, body elements are also subdivided into sectors to enable adequate simulation of asymmetric exposure scenarios.

The reference FPC passive system model resembles an average-population person based on analysis of anthropometric field surveys [22] which included older [50, 51] as well as recent, large-scale, studies [29, 53]. Thereby, the original (left-right symmetry) model consisting of 12 compartments [17] was refined to simulate the human body in greater detail consisting of 20 body elements. This so called '*reference*' human anthropometry model is an average, i.e. '50-percentile' (35 years old, unisex) 169.7 cm tall person weighting 71.4 kg (24.8 kg/m^2 body mass index).

It features a skin surface area of 1.83 m^2, body fat content of 22.6 %, and an average body density of 1.05 g/cm^3 [22]. The unisex anthropometry represents the average of a 50-percentile male and female person according to the above surveys which agree well also with other published data [52]. It was defined to (i) obtain a common basis for simulating individuals (see further below) and (ii) provide a well- defined reference model for simulating average-population responses in cases when no subject details are available or of interest.

The resultant anthropometric characteristics of the reference person are compared —in terms of relative body element lengths—with the corresponding field survey data and data employed in a biomechanical model of Daanen and Heerlen [8], in Table 1. The results agree with field survey data within 0.7 % deviation for main body parts. Larger discrepancies result for hands and feet as the incorporated thermal models required additional factors to be considered in order to simulate these body

Table 1 Comparison of relative body part lengths of the reference anthropometry model with the published data

Body part	NASA [50, 51]	Ansur I [29]	Daanen [8]	Ansur II [53]	Reference model
	%	%	%	%	%
Stature	100.0	100.0	100.0	100.0	100.0
Head + neck	14.5	13.5	17.4	13.7	13.9
Head to trunk	53.1	52.5	50.3	52.6	53.1
Trunk	38.7	39.0	28.0	38.9	39.2
Upper arm	18.4	19.5	17.4	18.9	19.0
Lower arm	15.9	15.2	15.7	15.2	15.6
Upper leg	20.2	20.5	24.0	20.5	20.4
Lower leg	22.9	23.2	25.1	23.2	22.7
Ankle (height)	3.7				3.7

parts adequately in thermophysiological terms [17]. Larger discrepancies result also for data used by Daanen and Heerlen due to the inherent differences in the definition of individual body parts in the thermal (FPC) and biomechanical models.

1.2 Scalable Anthropometry Model

The scalable anthropometry model was designed to be an easy-to-use model which, despite the complexity of the subject area, would only require the basic four individual parameters as model input, i.e. body height, weight, age, and gender. The scaling procedure employs the above *reference human anthropometry model* as a basis upon which the personal anthropometric characteristics of the person to be simulated are modelled. The individual parameters are then used to perform calculations of the overall and local body characteristics as indicated in Fig. 2.

To simulate an individual, body elements of the *Reference Model* are ‘scaled’ based on the four overall input parameters characterizing a person.

Results of anthropometric surveys indicate that the dimensions of individual body parts do not change uniformly as the stature varies. Tall subjects, for example, tend to feature longer extremities in proportion to the body height than smaller

subjects. In the model, the length of arms and legs is derived from the gender-specific length of the *tibia, femur, humerus* and *ulna* bones calculated as [51]:

$$L = a_1 H + a_0 \quad (1)$$

where L is the length of the bone in cm, H body height in cm, and a_1 and a_0 are the corresponding regression coefficients [50]. The remaining (cylindrical) body parts are scaled proportionally to changes in the body height while the trunk is sized to retain the body height of the simulated person.

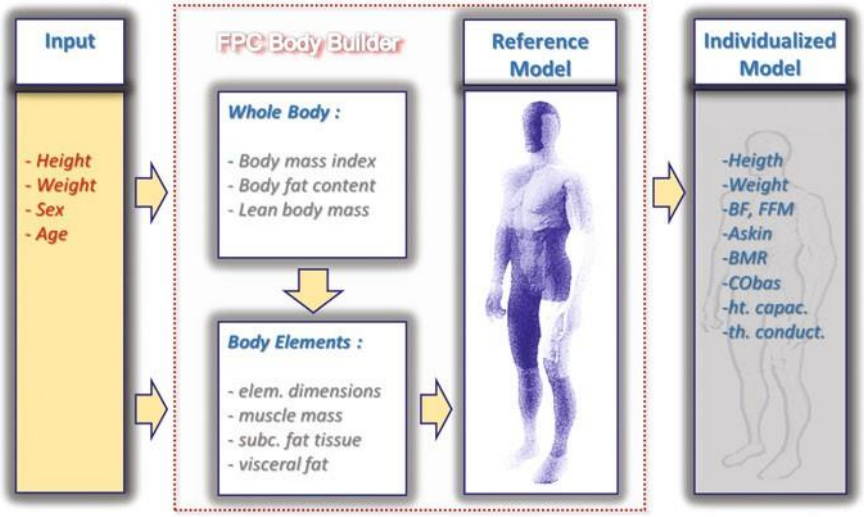

Fig. 2 Schematic diagram of the calculation process constituting the scalable FPC human anthropometry model

The predicted length of the main body sections are compared with measurements obtained from the CEASAR anthropometric survey [9, 59] for male subjects grouped in ten height categories ranging from 155 to 202 cm average height in Fig. 3. The predicted dimensions reproduce measured data within an overall average relative error of 1.8 %. The largest average relative error of 3.6 % resulted for upper legs. For lower legs, the crotch height, and the trunk the error was 1.1, 1.8 and 1.4 %, respectively. A similar level of accuracy was obtained also for upper extremities with 1.5 and 2.2 % average relative error for lower and upper arms, respectively [22].

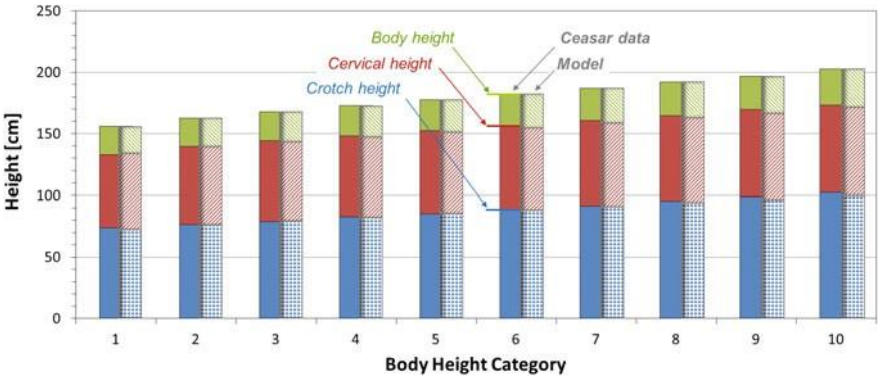

Fig. 3 Comparison of predicted body part lengths forming the stature with data obtained for male subjects from the CEASAR Project [9, 59] for 10 body height categories [22]

1.3 Body Composition

Body composition is another factor to consider in order to adequately represent a human in thermal simulations. The reference person was defined to represent an 'average' human with respect to the body dimensions, fat content, average tissue density, skin surface area, basal metabolic rate, cardiac output, as well as the overall body weight and body weight distribution. The relative weights of different body compartments, provided as percentages of the total body weight, are compared with the corresponding measured data in Fig. 4.

To simulate a person, not only his/her body dimensions but also the overall and local body properties have to be 'individualized' to fit the personal characteristics [22]. Thereby, the overall body fat content is either direct model input or is calculated according to Han and Lean [30] using the body mass index and the age of the simulated person:

$$\mathrm{BF} = c_{bf;b} \cdot \mathrm{BMI} + c_{bf;a} \cdot \mathrm{age} + c_{bf;0} \tag{2}$$

where BF is the body fat content in %, BMI body mass index in kg/m^2; and age in years. The coefficients $c_{bf,b}$, $c_{bf,a}$, and $c_{bf,0}$ with 1.330, 0.236 and −20.20 for males and 1.210, 0.262 and −6.70 for females, respectively, indicate significant differences in the body fat content among sexes [30].

Especially in males a notable portion of body fat may be retained as abdominal subcutaneous adipose tissue (ASAT) and visceral adipose tissue (VAT). VAT is determined based on Kuk et al. [44] who investigated the influence of the personal factors age and sex on VAT and ASAT in 483 young and older male and female subjects covering a wide range of body compositions. Taking into account the dependency of the waist circumference on the overall body fat content and age according to Han and Lean [30] the amount of the visceral adipose tissue is obtained as:

$$\mathrm{VAT} = \mathrm{BF}\,(\,c_{vat;bf\,0}+c_{vat;bfa}\,\mathrm{age}) + \;c_{vat;aa}\,\mathrm{age}^2 + c_{vat;a}\;\mathrm{age} + c_{vat;0} \tag{3}$$

where VAT is visceral fat tissue in kg and BF body fat content in % body weight. The coefficients $c_{vat,bf0}$, $c_{vat,bfa}$, $c_{vat,aa}$, $c_{vat,a}$, and $c_{vat,0}$ are gender specific with

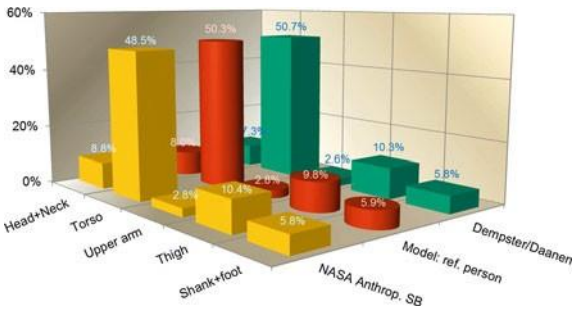

Fig. 4 Comparison of relative body part weights: model (reference person) versus measured data [8, 50]

0.459, 0.003, 0.0003, −0.071 and 12.892 for males and −0.005, 0.003, 0.0008, −0.076 and 0.529 for females, respectively.

The abdominal subcutaneous fat content is calculated similarly based on experimental results of Kuk et al. [44] and Han and Lean [30]:

$$\mathrm{ASAT} = c_{as;b}\,\mathrm{BF} + c_{as;a}\,\mathrm{age} + c_{as;0} \tag{4}$$

where ASAT is the amount of abdominal subcutaneous fat in kg. The coefficients $c_{as,b}$, $c_{as,a}$ and $c_{as,0}$ are 0.194, 0.020, and −1.400 for males and 0.251, 0.055 and −3.387 for females, respectively.

An iterative procedure distributes the overall quantities to obtain local adipose and fat-free mass portions by scaling the thickness of local subcutaneous fat tissue layers relative to the corresponding proportions of the reference model. This approach recognizes that while the largest portion of the body fat is contained in central body parts, the remainder is distributed with decreasing share over proximal limbs towards the outer extremities and the head [13].

The individualized properties are 'mapped' onto individual body elements of the reference model resulting in an updated numerical representation of the human body in the model. As illustrated in Fig. 5, the model's resultant total body fat content after iterative scaling and integration reproduces experimentally based values [30] with and average error of 0.56 % for a wide range of body height and fat content combinations.

It should be noted that the scaling processes not only changes the anthropometric and morphological body characteristics but indirectly changes also other important body properties including e.g. the basal metabolic rate and skin surface area. According to WHO [67], the basal metabolic rate of males and females varies in

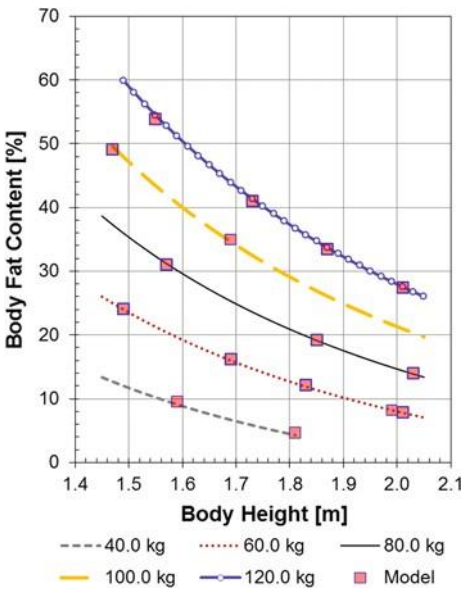

Fig. 5 Comparison of model's body fat content with experimentally derived data as a function of body height and body weight obtained for male (35 years old) subjects [22, 30]

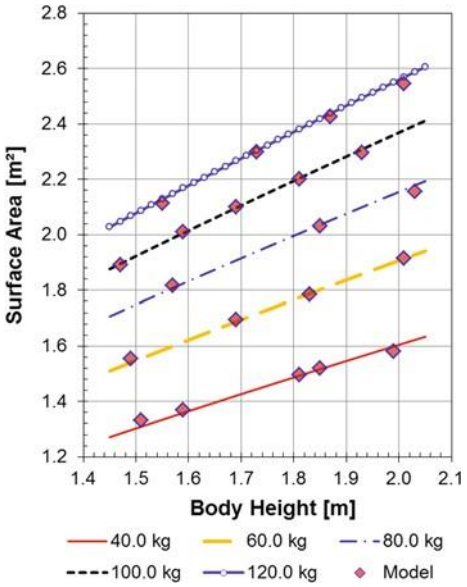

Fig. 6 Model's total skin surface area as a function of body height and weight obtained for male (35 years old) subjects compared with experimentally based data [12, 22]

proportion to body weight though with significant differences among sexes. The scalable model reproduces the WHO formula model within 5 % relative error for both sexes. The overall skin surface area affects the heat exchange with the environment and thus has important implications also for temperature regulation. The total skin surface area which results from the above scaling processes is compared with the Dubois body surface area [12] for different combinations of body height and weight in Fig. 6. It reproduces the Dubois formula with an average error of 0.010 ± 0.008 m^2.

1.4 Tissue Heat Transfer

Pennes formulated the so called bioheat equation to describe the dynamic heat transfer processes that occur within living tissues [54]. Extended for heat dissipation in spheres in the model (head), the differential equation can be written as:

$$\rho c \frac{\partial T}{\partial t} = k\left(\frac{\partial^2 T}{\partial r^2} + \frac{\omega}{r}\frac{\partial T}{\partial r}\right) + q_m + c_{bl}\ \rho_{bl}\, w_{bl}(T_{bla} - T) \qquad (5)$$

where ρ, c, and k are tissue density (kg m^{-3}), heat capacitance (J kg^{-1} K^{-1}) and conductivity (W m^{-1} K^{-1}), respectively. T is the tissue temperature (°C), t time (s), r radius (m); ω a geometry factor (ω = 1: polar, ω = 2: spherical co-ordinates), q_m metabolic heat generation (W m^{-3}), ρ_{bl} blood density (kg m^{-3}), w_{bl} blood perfusion rate (m^3 s^{-1} m^{-3}), c_{bl} heat capacitance of blood (J kg^{-1} K^{-1}), and T_{bla} (°C) arterial blood temperature.

In the numerical model, tissue layers are discretized as nodes using a numerical form of the bioheat equation that employs a finite-difference (*Crank-Nicholson*) scheme [17]. Applied to a tissue node n (with $n - 1$ and $n + 1$ being the preceding and succeeding adjacent nodes, respectively) and separating the (unknown) 'future'

temperature terms ($t + 1$) the numerical form of the general bioheat equation yields:

$$\begin{aligned}
&[\gamma_n - 1]\, T_{n-1}^{(t+1)} + \left[\frac{\zeta_n}{\Delta t} + 2 + \delta_n\, \beta_n^{(t+1)}\right] T_n^{(t+1)} - [1 + \gamma_n]\, T_{n+1}^{(t+1)} - \delta_n\, \beta_n^{(t+1)}\, T_{bla}^{(t+1)} \\
&= [1 - \gamma_n]\, T_{n-1}^{(t)} + \left[\frac{\zeta_n}{\Delta t} - 2 - \delta_n\, \beta_n^{(t)}\right] T_n^{(t)} \\
&\quad + [1 + \gamma_n]\, T_{n+1}^{(t)} + \delta_n \left[q_{m,n}^{(t+1)} + q_{m,n}^{(t)}\right] + \delta_n\, \beta_n^{(t)}\, T_{bla}^{(t)}
\end{aligned} \tag{6}$$

where

$$\gamma_{n(cyl.)} = \frac{\Delta r_n}{2 r_n};\ \gamma_{n\ (sph.)} = \frac{\Delta r_n}{r_n};\ \zeta_n = 2\Delta r_n^2 \frac{\rho_n\, c_n}{k_n};\ \delta_n = \frac{\Delta r_n^2}{k_n}. \tag{7}$$

The time step Δt (s) approximates the differential dt, and β_n ($Wm^{-3}K^{-1}$) represents a time-dependent calorimetric equivalent of the nodal blood flow rate:

$$\beta_n = \rho_{bl}\, c_{bl}\, w_{bl,\,n} \tag{8}$$

Applying Eq. 6 to each tissue node of the numerical model with the corresponding material properties, nodal heat generation and blood perfusion rates, constitutes a system of coupled linear equations which is to be solved for each time and iteration step of a simulation [17]. Solving the whole body matrix for the (undressed) reference person exposed to thermo-neutral, steady state (still air) environmental conditions of 30 °C, 50 % RH results in a mean skin temperature of 34.3 °C and body core temperatures of 37.0 °C in the head core (hypothalamus) and 36.9 °C in the abdomen core (rectum). The resultant overall physiological data replicate a reclining subject with an overall basal body metabolism of 75.5 W, basal evaporation (i.e. moisture diffusion) rate from the skin of 19 W, and basal cardiac output of 4.9 L min^{-1} [22].

The q_m-term in Eq. 6 is a sum of the local tissue's thermo-neutral basal metabolic rate, $q_{m,0}$ ($W\ m^{-3}$) and any additional heat gain, Δq_m ($W\ m^{-3}$):

$$q_m = q_{m;0} + \Delta q_m \tag{9}$$

Δq_m includes variations in basal metabolism due to changes in tissue temperature from the local setpoint, T_0, which refers to the above conditions of thermal neutrality. In muscles, additional heat may be generated by exercise, $q_{m,w}$, or by regulatory shivering, $q_{m,sh}$, as local portions of the respective overall quantities:

$$\Delta q_m = q_{m,0}\left(2^{\frac{T-T_0}{10}} - 1\right) + q_{m,w} + q_{m,sh} \tag{10}$$

Similarly to q_m, local tissue blood perfusion rates, w_{bl}, are defined as a sum of the thermo-neutral basal rate $\beta_{m,bas,0}$ ($Wm^{-3}K^{-1}$) and variations $\Delta\beta_{bl}$ ($Wm^{-3}K^{-1}$):

$$\beta_{bl} = \beta_{bl,0} + \Delta\beta_{bl} \tag{11}$$

the latter being proportional to changes in the local metabolic rate: $\Delta\beta_{bl} = 0.932\Delta q_m$ [64]. The largely variable blood flows within the cutaneous plexus are subject to central nervous system regulation as described further below.

Blood circulation plays a dominant role in the human heat transfer. In the passive system model, each body element is supplied with arterial blood from the central pool (heart). Before perfusing local tissues, blood is 'conditioned' by counter-current blood streams of adjacent veins. Arterial blood at local arterial temperatures perfuses then tissues exchanging heat in the capillary beds where, according to Eq. 5, it reaches equilibrium with local tissues. Depleted blood is then collected in veins being re-warmed by counter-current heat exchange with adjacent arteries as it flows back to the central pool. Finally, venous blood from the whole body is mixed in the central blood pool perfusing the lung to constitute a new central blood pool temperature.

The blood perfusion term in Eq. 5 only accounts for heat exchange with tissues in the capillary bed. In the model also counter-current heat exchange between pairs of adjacent arteries and veins is considered [17]. The net heat exchange between adjacent vessels, Q_x (W) is expressed as [28]:

$$Q_x = h_x(T_{bla} — T_{blv}) \tag{12}$$

where h_x (WK^{-1}) is the counter-current heat exchange coefficient [24]. These coefficients are equal to zero in central body parts and are >0 in extremities. In the individualized model they vary with the length of individual extremities.

Considering the counter-current heat exchange between adjacent vessels, the heat loss from an artery equals the heat gain of the adjacent vein. Assuming mass-continuity in blood vessels, the decrease in arterial blood temperature, $T_{blp} - T_{bla}$ is thus equal to the rise of venous blood temperature, $T_{blvx} - T_{blv}$, after passing the counter-current heat exchanger [17]:

$$\sum_{i}^{nodes} \beta_i V_i \left(T_{blp} - T_{bla}\right) = \sum_{i}^{nodes} \beta_i V_i \left(T_{blvx} - T_{blv}\right) \tag{13}$$

where T_{blp} (°C) is the central blood pool temperature, V_i (m^3) tissue nodal volume, and T_{blv} (°C) and T_{blvx} (°C) is the body element's venous temperature before and after passing the counter-current heat exchanger, respectively. Since the bioheat Eq. 5 assumes capillary blood to reach equilibrium with the surrounding tissues, T_{blv} yields:

$$T_{blv} = \frac{\sum_i^{nodes} T_i \beta_i V_i}{\sum_i^{nodes} \beta_i V} \tag{14}$$

With the above equations the local arterial blood temperature, T_{bla}, (°C) of a body element can be calculated as:

$$T_{bla} = \frac{T_{blp} \sum_i^{nodes} \beta_i V_i}{h_x + \sum_i^{nodes} \beta_i V_i} + \frac{\frac{h_x}{\rho_{bl} c_{bl}} \sum_i^{nodes} T_i \beta_i V_i}{\sum_i^{nodes} \beta_i V_i \left(h_x + \sum_i^{nodes} \beta_i V_i\right)} \tag{15}$$

The blood pool temperature, T_{blp}, is a function of local tissue temperatures from all body parts:

$$T_{blp} = \frac{\sum_k^{b.elem.} \left(\frac{\sum_i^{nodes} \beta_{k,i} V_{k,i}}{h_{x,k} + \sum_i^{nodes} \beta_{k,i} V_{k,i} \sum} \times \sum_i^{nodes} T_{k,i} \beta_{k,i} V_{k,i} \right)}{\sum_k^{b.elem.} \left[\frac{\left(\sum_i^{nodes} \beta_{k,i} V_{k,i} \right)^2}{h_{x,k} + \sum_i^{nodes} \beta_{k,i} V_{k,i}} \right]} \tag{16}$$

2 Modelling the Active System

2.1 Concept and Model Definition

The active system is a cybernetic model of human thermoregulation that simulates the four essential responses of the central nervous system: production of sweat moisture, *Sw*, increase of metabolic heat generation in muscles due to shivering, *Sh*, and changes in cutaneous blood flows due to peripheral vasodilatation, *Dl*, and vasoconstriction, *Cs*. The implemented concept adopts principles of a set-point temperature based control system that has been formulated and implemented previously in other models (e.g. [25, 26, 64]). Set-point based systems define regulatory stimuli generating afferent signals as 'error' signals, i.e. the difference between a variable of the actual thermal state, x (e.g. temperature) and the corresponding setpoint that refers to conditions of thermal neutrality (see Sect. 2.4), x_0:

$$\Delta x = x - x_0 \tag{17}$$

Rather than using postulative methods, meta-regression analysis was employed to define a statistically founded reference active system [18] for simulating responses of an 'average' person. Thereby, published experimental studies were simulated and measured regulatory responses were correlated with predicted afferent signals to (i) investigate their involvement and responsibility in each response based on their statistical significance and to (ii) formulate the governing

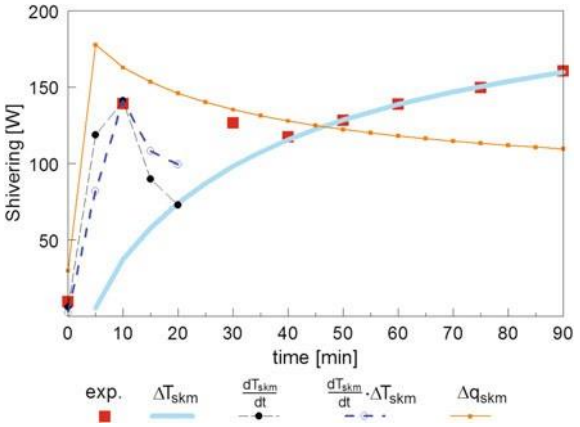

Fig. 7 Example of linear regression lines as functions of different afferent signals to predict the shivering response observed in semi-nude reclining subjects (exp.) suddenly exposed to a cold environment of 5 °C. Adopted from [18] with permission

regulatory equations. Considered were established signals associated with skin temperatures (ΔT_{skm}), head core (hypothalamus) temperatures (ΔT_{hy}), rates of change of skin temperature (dT_{skm}/dt) as well as theoretical signals associated e.g. with muscle temperatures or skin heat fluxes (Δq_{skm},), Fig. 7.

Overall, the regression studies confirmed the body core (hypothalamus) temperature, T_{hy}, and (mean) skin temperature, T_{skm}, to be the main driving impulses for human thermoregulatory action. A further signal, i.e. rate of change of the skin temperature, dT_{skm}/dt, weighted by the error signal associated with the skin temperature, was identified as the driving impulse that governs the dynamics of regulatory responses during rapid skin cooling such as the typical shivering 'overshoot' (e.g. Fig. 7). A schematic diagram of the reference active system model is provided in Fig. 8.

The analysed conditions included 26 different experiments covering exposures to steady state and transient environments ranging from cold, over moderate to heat stress conditions and physical activities from reclining to intense exercise [18]. The results obtained for all exposures were then subjected to meta-regression analysis to study the consistency and functional dependencies of the linear regression coefficients on the subjects' thermal state. The coefficients for individual responses are plotted together with the respective fitting non-linear functions in Fig. 9.

With the dynamic term for skin cooling, i.e. negative rates of change of skin temperature, $dT_{skm}^{-}=dt$, and (the statistically significant) temperature error signal from the head core included, the control equation for shivering, Sh (W), yields:

$$Sh = 10[\tanh(0.48\Delta T_{skm} + 3.62) - 1]\Delta T_{skm} - 27.9\Delta T_{hy} + 1.7\Delta T_{skm} \times \frac{dT_{skm}^{-}}{dt} - 28.6 \quad (18)$$

The Sh–response is limited to a maximum of 350 W in the model [18]. The response is compensated by any extra metabolism due to exercise, $q_{m,w}$, and is distributed over body regions using distributions coefficients, c_{sh} [18].

The overall sweat excretion rate, Sw (g min^{-1}), is predicted as:

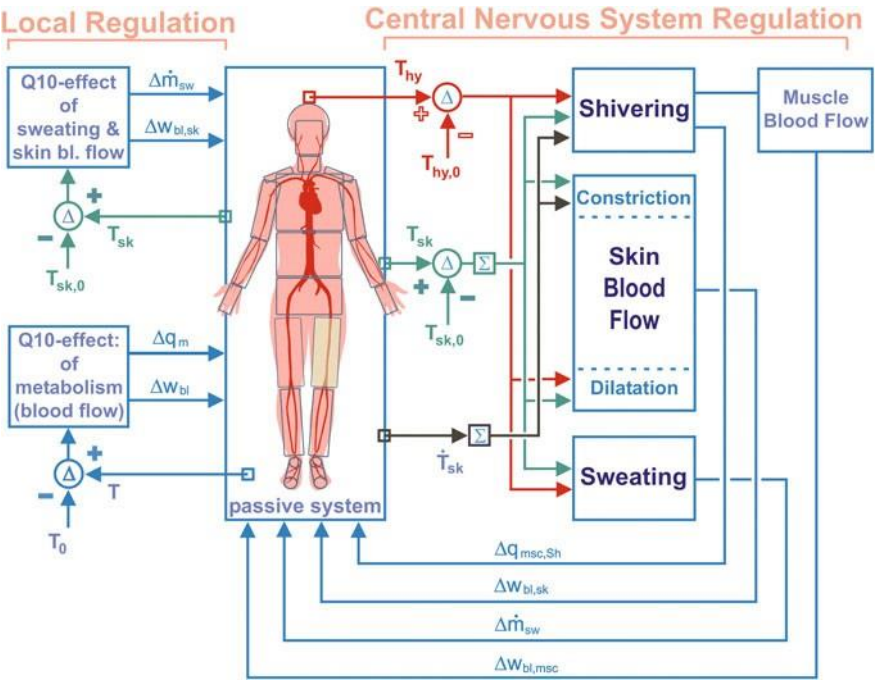

Fig. 8 Schematic diagram of the reference active system model. *Left* responses of local autonomic control; *right* responses of the central nervous system regulation accounting for overall changes in muscle metabolism by Shivering, *Sh*, (and the corresponding changes in muscle blood flow), skin moisture excretion by sweating, *Sw*, and skin blood flow by peripheral vasodilatation, *Dl*, and constriction, *Cs*. The model uses temperatures of the skin (T_{sk}) and of head core (T_{hy}) as well as the rate of change of skin temperature as input signals into the regulatory centre. Setpoint temperatures $T_{sk,0}$, T_0 and $T_{hy,0}$ refer to the nude reclining body's thermo-neutral state at 30 °C operative temperature

$$Sw = [0.8\tanh(0.59\,\Delta T_{skm} - 0.19) + 1.2]\,\Delta T_{skm} + \left[5.7\tanh\left(1.98\Delta T_{hy} - 1.03\right) + 6.3\right]\Delta T_{hy} \tag{19}$$

An upper limit for *Sw* of 30 g min^{-1} applies as a typical maximum rate for an average person [18] in the reference active system model. The resultant, local sweat rates, dm_{sw}/dt (g/min), are obtained as portions of *Sw* distributed over body parts using coefficients, c_{sw} [24], and being weighted by local influences of the Q10-effect due to local skin temperatures deviations from setpoints, $T_{sk,0}$ [18, 48] and local skin wettedness, f_{wsk} [6, 49]:

$$\frac{dm_{sw}}{dt} = c_{sw} f_{wsk} Sw \times 2^{\frac{T_{sk}-T_{sk,0}}{10}} \tag{20}$$

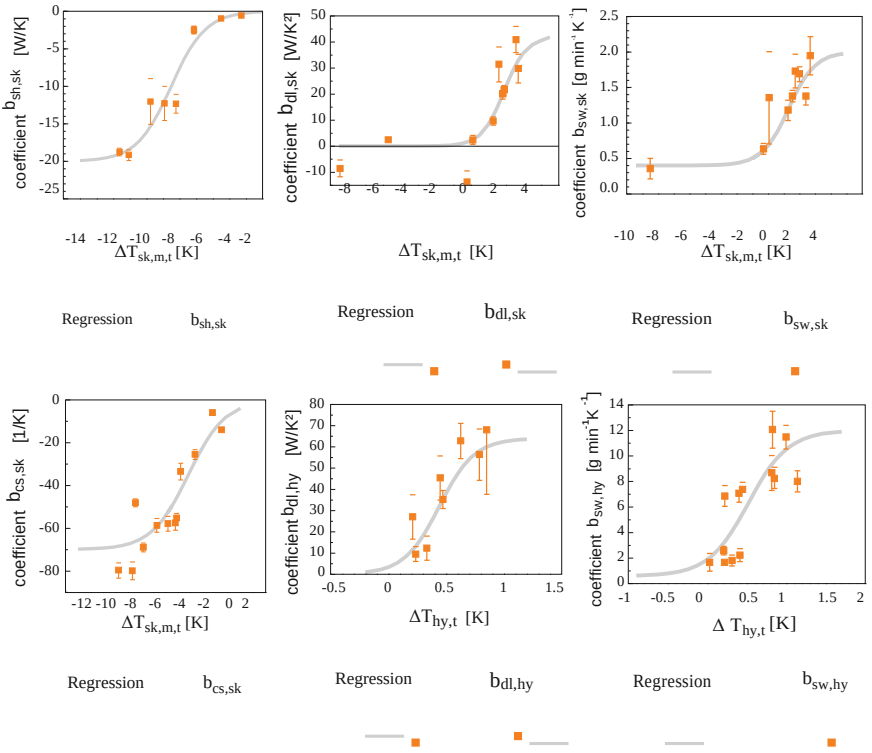

Fig. 9 Dependency of linear regression coefficients *b* obtained for different exposures on skin and head core temperature levels, i.e. error signals ΔT_{sk} and ΔT_{hy} obtained for the *Sh*-, *Sw*-, *Dl*-, and *Cs*-response, and the corresponding fitting functions (adopted from [18] with permission)

No statistically significant effect of the body core temperature was found in the response of peripheral vasoconstriction, *Cs* [−]. The control equation thus only includes static and dynamic afferent signals associated with the skin temperature:

$$Cs = 35[\tanh(0.34\Delta T_{skm} + 1.07) - 1]\Delta T_{skn} + 6.8\Delta T_{skm}\frac{dT^{-}_{skm}}{dt} \tag{21}$$

In contrast to constriction, vasodilatation, Dl (W K^{-1}), is regulated by statistically significant afferent signals associated with both the skin and body core temperature in the model:

$$\begin{aligned} Dl = {} & 21[\tanh(0.79\Delta T_{skm} - 0.70) + 1]\Delta T_{skm} \\ & + 32\left[\tanh\left(3.29\Delta T_{hy} - 1.46\right) + 1\right]\Delta T_{hy} \end{aligned} \tag{22}$$

The resultant local blood perfusion rates, w_{bl}, within the skin are obtained as local portions c_{dl} and c_{cs} [24] of the overall vasomotor responses also being modulated by local skin temperatures:

$$\beta_{sk} = \frac{\beta_{sk,0} + c_{dl}\, Dl}{1 + c_{cs} Cs \cdot e^{-Dl/80}} \times 2^{\frac{T_{sk} - T_{sk,0}}{10}} \tag{23}$$

Literature indicates a maximum skin blood flow that varies with the type and level of exercise [61]. In the model, the maximum overall skin blood flow, $B_{sk,\max}$ (W K^{-1}), decreases in proportion with any overall increase in muscle blood flow, ΔB_{msc} (W K^{-1}) [18]:

$$B_{sk;\max} = 386.2 - 0{:}32 \times \Delta B_{msc} \quad (24)$$

If the sum of all local blood flows in the skin as prescribed by Eq. 23 exceeds $B_{sk,\max}$ at any exercise condition then the local rates are trimmed in proportion to $B_{sk,\max}$ in the model.

2.2 Personalized Thermoregulation

Human thermoregulatory responses are known to be affected by personal characteristics such as gender, age, physical fitness, anthropometry and body composition, acclimatisation, etc. Of the various personal characteristics there are four main factors which affect the human individual heat stress response [33]: aerobic fitness, acclimatization, and anthropometric and morphological properties of the body. Other factors including age and gender lose their influence when 'correcting' observed responses for the effect of the maximum aerobic power, $VO_{2,\max}$, and the body fat content [33].

Of the four main personal factors the individualized passive system described above implicitly accounts for the effect of a person's anthropometry and morphology including related factors involved in the environmental heat exchange, e.g. skin surface area, bodily thermal insulation (fat content), heat capacity (body mass), and the body surface-to-volume ratio.

The individual heat stress response model of Havenith [34] was adapted for use with the FPC-model to account for the effect of the remaining two personal factors, i.e. the aerobic fitness and acclimatization status. Personal parameters that directly and indirectly affect responses of the active system model are depicted in Fig. 10.

The approach is based on the assumption that individual variations in thermoregulatory responses are associated with a shift of the setpoint of the body core temperature, i.e. hypothalamus temperature in the FPC-model, $DT_{hy,set}$ (°C):

$$T_{hy,set} = T_{hy,set;0} - \Delta T_{hy,set} \quad (25)$$

where $T_{hy,set}$ (°C) is the adapted setpoint temperature, and $T_{hy,set,0}$ (°C) the setpoint temperature of the reference active system simulating an 'average' person. According to Havenith [34] the shift is a function of the physical fitness, fit, and the acclimatization status, F_{ac}:

$$\Delta T_{hy,set} = 0.1 \times \frac{fit}{10} + 0.25 \times F_{ac} \quad (26)$$

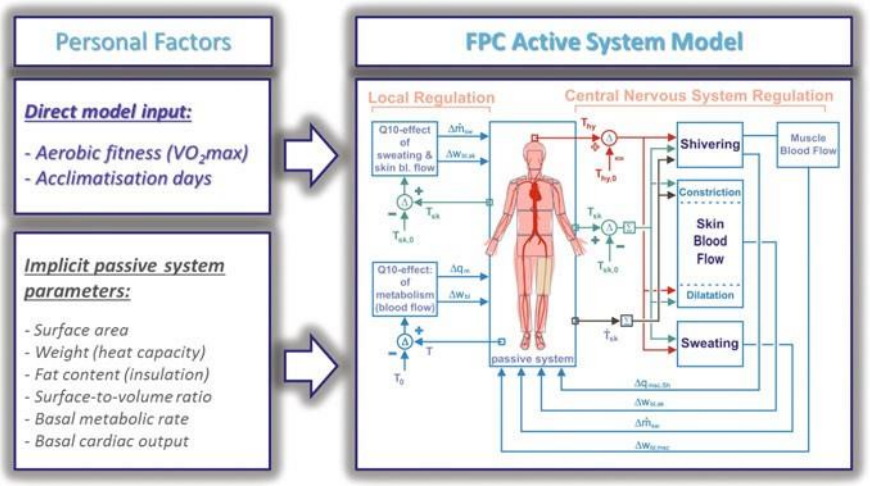

Fig. 10 Personal factors used as 'direct' and 'indirect' (passive system variations) input into the active system model to simulate responses of individuals

The personal fitness, fi*t*, is dealt with in terms of the individual maximum aerobic power, $VO_{2,\max}$ (ml kg^{-1}min^{-1}) as direct model input. The difference between the individual and the average maximum aerobic power of an average-fit person, i.e. 40 ml kg^{-1}min^{-1}, is used as a measure of the individual fitness, fi*t*:

$$fit = VO_{2;\max} - 40 \tag{27}$$

where $VO_{2,\max}$ may vary between $20 \le VO_{2,\max} \le 60$ ml kg^{-1}min^{-1} for unfit and trained individuals, respectively [34]. Quantities exceeding these limits are trimmed accordingly in the model.

The acclimatization status, F_{ac}, is a function of the number of acclimatization days, n_d:

$$F_{ac} = 1 - \exp(-0{:}3\, n_d) \tag{28}$$

Thereby the number of acclimatization days, which is another direct input parameter, varies between $0 \le n_d \le 14$ days in the model [34].

The central effector outputs for sweating, *Sw*, and vasodilatation, *Dl*, are computed as in the reference model by Eqs. 19 and 22, respectively, but using modified afferent signals from the head core, i.e. $D T_{hy} = T_{hy} - T_{hy,set}$ with T_{hy} being the actual head core temperature and $T_{hy,set}$ the corresponding modified setpoint temperature, Eq. 25. If both fi*t* and F_{ac} are zero also $D T_{hy,set}$ is zero and the original setpoint temperature of 37.0 °C applies. However, any shift $D T_{hy,set} > 0$ causes a shift of the onset of sweating and skin blood flow towards lower body core temperatures and vice versa.

In addition to the shift of the body core temperature setpoint due to acclimatization and physical fitness, the gain factor, g_{sw}, influences the sweating response in the individualized model:

$$g_{sw} = \left(1 + 0.35 \times \frac{fit}{20}\right) \times (1+0.15 \times F_{ac}) \tag{29}$$

g_{sw} modulates the sweating response, Sw, predicted by Eq. 19 to obtain the individualized response, Sw_{ind} (g min^{-1}):

$$Sw_{ind} = Sw \times g_{sw} \tag{30}$$

The reference upper limit for sweating, Sw_{max}, of 30 g min^{-1} is also subject to personal variations which is accomplished using the factor $f_{sw,max}$:

$$f_{sw,max} = 1 + 0.25 \times \frac{fit}{20} + 0.25 \times F_{ac} \tag{31}$$

with $f_{sw,max}$ the individual maximum sweat rate, $Sw_{max,ind}$ (g min^{-1}) yields:

$$Sw_{max,ind} = Sw_{max} \times f_{sw,max} \tag{32}$$

In the model the maximum overall skin blood flow, $B_{sk,max}$, is not constant but varies with the intensity of exercise. The individualized maximum is derived from $B_{sk,max}$ using the factor $f_{Bsk,max}$ which is a function of the aerobic fitness and acclimatization status:

$$f_{Bsk,max} = 1 + 0.25 \times \frac{fit}{60} + 0.25 \times F_{ac} \tag{33}$$

For any activity level, the individualized overall maximum skin blood flow, $B_{sk,max,ind}$ (W K^{-1}) then yields:

$$B_{sk;max;ind} = B_{sk;max} \times f_{Bsk;max} \tag{34}$$

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