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Modeling heat loss through sweating: Towards improved heat load prediction from child occupants

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ABSTRACT

The design of HVAC systems requires correct estimation of both sensible and latent heat gains from occupants in order to assess cooling loads. Children differ significantly from adults in their heat production and thermoregulation in part due to variations in body mass, height, and sweat gland development, resulting in a unique sensible heat ratio for children. Though in spaces such as school classrooms and gymnasiums or daycares, children are the dominant occupant group, they are absent from load tables documenting the rate of net heat production by occupants and their sensible heat ratio. This study presents a steady-state, child-specific heat balance model, developed by modifying existing first-order thermodynamic equations from the literature to account for children's unique anthropometric characteristics. Through a comprehensive search process, experimental data on children's heat loss through sweating was gathered and analyzed. Statistical analysis of this data revealed the shortcomings of adult-based models in calculating the rate of evaporative heat loss through sweating per body surface area of children, even in mild environmental conditions. A novel regression model of the evaporative heat loss through sweating as a function of the air dry bulb temperature and net heat generation is proposed. This research lays the groundwork for the creation of comprehensive child-specific heat load tables, essential for optimizing HVAC systems in spaces designed for children.

1. Introduction

As heat, air and moisture control in building assemblies improve, the influence of internal heat gains on cooling load calculations has increased. The net heat generated by occupants, commonly used in thermal comfort calculations [2,3], is also important in the design of building HVAC (heating, ventilation, and air conditioning) systems [2,3]. Determining zone cooling loads requires a distinction be made between the sensible and latent loads generated by occupants of a space. The total rate of evaporative heat loss (E, in W/m^2) and total rate of dry heat loss (D, in W/m^2), from a source is usually determined through knowledge of the net heat it generates and its sensible heat ratio (*SHR*, unitless) [3]. Commonly used load tables [1] provide distinct sensible and latent loads for adult occupants performing various common indoor activities, ranging from 'seated at theater' to 'athletics' in a gymnasium.

Children have significantly different heat generation and thermoregulation responses from adults, especially at a young age [4]. Children[1] generate less heat (in watts) than adults for the same activity, due to having a lower body mass and height [2,5]. Extensive research exists to document net heat given off by children performing different common tasks [2,5,6]. But there are also major differences in how they dissipate this heat. Children have a higher body surface area to mass ratio [4], which gives them an advantage for sensible heat dissipation. Conversely, their smaller and underdeveloped sweat glands put them at a disadvantage for evaporative heat loss [4,6]. All of this renders them uniquely different heat sources than adults, and points at a distinctly different sensible heat ratio (*SHR)* for these two populations. Yet, commonly used load tables [1] only indicate that heat gain from a child are assumed to be "75 % of that of an adult male", implying the same *SHR* should be used.

Though no study could be found specifically documenting the *SHR* of children, studies have analyzed the differences in their heat dissipation mecanisms and contrasted their thermoregulatory response to those of adults. Many such studies were conducted in hot and/or dry environments, with subjects performing intense physical activity to induce sweating, in order to analyze the difference in the resultant heat loss through sweating between children and adult subjects. Davies et al. [7]

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[1] The age range for which one is defined as a 'child' varies across countries. In this paper, we will use the term 'children' in reference to pre-pubertal and mid-pubertal persons.

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Nomenclature

A_D	DuBois surface area, m^2
BMR	basal metabolic rate, W
E	total rate of evaporative heat loss, W/m^2
C	rate of heat loss by convection from the outer surface of the clothed body, W/m^2
C_{res}	rate of convective heat loss from respiration, W/m^2
D	total rate of dry heat loss, W/m^2
E_{sk}	total rate of evaporative heat loss from skin, W/m^2
E_{dif}	rate of evaporative heat loss by water vapor diffusion through the skin, W/m^2
E_{rsw}	rate of evaporative heat loss from the skin due to sweating, W/m^2
E_{res}	rate of evaporative heat loss from respiration, W/m^2
EE	energetic equivalent, W·h/l O_2
f_{cl}	clothing area factor, unitless
H	net rate of heat production, W/m^2
H''	absolute net rate of heat production, W
h	combined heat transfer coefficient of convection and radiation, W/m^2·K
h_c	convective heat transfer coefficient, W/m^2·K
h_r	linear radiative heat transfer coefficient, W/m^2·K
h_{fg}	latent heat of vaporization of water, J/kg
l	height, cm
M	rate of metabolic heat production, W/m^2
MET_y	youth *MET*, a metric expressing the energy cost of physical activitie as multiple of *BMR* for youths, unitless
m	body mass, kg
m_{H2O}	water amount on the skin, g/m^2
$m_{H2O,\max}$	maximum amount of water on the skin, g/m^2
m_{int}	subject initial mass, kg
m_{fin}	subject final mass, kg
m_{fl}	fluid intake mass. kg
m_u	fluid loss through urination mass, kg
m_{cl}	change in the mass of clothes, kg
m_{ge}	respiratory water loss mass, kg
m_p	permeance coefficient of the skin (kg/hr·m^2·kPa)
m_{rsw}	amount of sweat generated, kg
$\dot{m}_{rsw}$	rate at which regulatory sweat is generated, kg/s·m^2
m_{sk}	mass of water loss during exercise, kg
$\dot{m}_{sk}$	the rate of water loss during exercise, kg/s·m^2
$p_{sk,s}$	saturated vapor pressure at skin temperature, kPa
p_a	vapor pressure at ambient temperature, kPa
q_{sk}	total rate of heat loss from skin, W/m^2
q_{res}	total rate of heat loss through respiration, W/m^2
R	rate of heat loss by radiation from the outer surface of the clothed body, W/m^2
R_{cl}	thermal resistance of clothing, m^2·K/W
RH	relative humidity, %
RQ	Respiratory quotient, unitless
SHR	sensible heat ratio, unitless
T_{db}	air dry bulb temperature, °C
T_{sk}	skin temperature, °C
T_{cr}	core temperature, °C
T_{wb}	air wet bulb temperature, °C
VO_2	oxygen uptake per kilogram of body mass, mL/kg·min
$VO_{2,\max}$	peak oxygen uptake per kilogram of body mass, mL/kg·min
W	rate of mechanical work accomplished, W/m^2
W_a	air absolute humidity, kg/kg
W_{ex}	absolute humidity of expired air, kg/kg
w	skin wettedness, unitless
w_{rsw}	skin wettedness due to regulatory sweat, unitless
v	air velocity, m/s

compared the thermal response of prepubertal boys, adolescent girls, and adult men performing high intensity activity in standard environmental conditions, their results indicate a children's *SHR* of 0.44, while it was 0.33 for adults under the same conditions. Inbar et al. [8] compared the sweating rate between prepubertal boys, adult men, and elderly men exercising in a dry hot environment. Their data results in a *SHR* of 0.23 for the boys and 0.15 for the men in the same environment. Children's reduced reliance on evaporative heat loss in their thermoregulation was also confirmed by Drinkwater et al.[9], Falk et al. [10], Meyer et al. [11], Delamarche et al. [12], Arlegui et al. [13], Araki et al. [14], and Wagner et al. [15]. These findings indicate that whether in standard environments or in hot and dry environments (i.e., more likely to induce sweating), children rely less on evaporative heat loss for thermoregulation, and should therefore have, in the same environment, a different *SHR* than adults. While some studies have determined and tabulated the internal heat generated by child subjects performing specific activities [2,5,6], no resource exists that allows rapid determination of *SHR* generated by this occupant population, as needed for HVAC design applications.

A general heat balance model that has been experimentally validated for children in a broad range of indoor environmental conditions does not yet exist. Fanger [16] developed a heat balance model for occupants in indoor environments based on experimental data gathered from adult subjects in thermal comfort conditions. Though used extensively in the scientific literature, thermal comfort modeling software, norms and guidelines pertaining to adults, it is limited to that population and has not been validated for children. Other models have been developed for hotter environments more conducive of sweating [17–20], however they were not developed nor validated for children's sweat response. Other models which have been developed with child subjects in mind [21], or used in research on children's thermal comfort [22,23], cannot reliably provide the *SHR* ratio coveted. Validation of Cheng et al.'s COMFA-kid model [21] was accomplished by comparing the predicted thermal sensation vote (*TSV*) of child subjects in sun-exposed outdoor environments, to the actual *TSV* of child subjects. However, the model uses a single equation to calculate the total heat from respiration, with no separation of latent and sensible loss, which renders it impossible to use to determine *SHR*. Schlabach et al. [23] and McCullough et al. [22] developed child models intended for use in cold outdoor environments where sweating is not likely to occur; their ability to determine the *SHR* investigated is improbable. THERMODE 2023 [19], a detailled multi-cylinder transient model, has been shown to reliably predict skin temperature (T_{sk}), core temperature (T_{cr}), and *TSV* of occupants in moderate environments. Its thermal sensation model has been validated agains the responses of 4416 students aged 11 to 18 years old. Yet, its approach to calculating evaporative heat loss (E) or its components (ie. E_{res}, E_{rsw}, E_{dif}) has not been validated for this population. Fiala et al. [24] presented a transient, multi-segmented and multi-layered model which relied on empirical regressions to determine the thermophysiological control mecanisms of sweat response of adults from T_{sk} and head core temperature. The model has been extensively validated against experimental data on adult participants [24] but not on children. Much recent thermoregulation models have become more and more detailled: they represent the human body in three-dimensions, include active and passive components, consider transient and/or asymetric environmental conditions. This increases their computational time, requires important adjustments to implement adequate population caracteristics, and renders them unwieldy for long-term simulation [19], which likely explains why common building performance simulation software such as EnergyPlus still relies on steady-state whole-body models or two-node models for thermal comfort calculations and occupant load calculations [25].

Therefore, the goal of this paper is to develop a heat balance model for child occupants in indoor environments that is simple enough to be used in building performance simulation software, yet can be relied upon to provide the *SHR* for said occupants performing various indoor activities. The general steady state heat balance used in this model is based on the first-principles equations proposed by Fanger [16] and used by ASHRAE [3] but adjusted with child-specific anthropometric data collected from the literature. In the case of the rate of evaporative heat loss through sweating (E_{rsw}), Fanger's empirical approach establishing a relationship between E_{rsw} and the activity level was adopted. Novel regression models for E_{rsw} are developed based on child data from literature, instead of applying Fanger's existing experimental regressions which are strictly based on adult data. The results of this paper will allow the prediction of heat loads from and thermal comfort of child occupants in building performance simulation software and pave the way for the development of child-specific heat load tables. Engineers can use these tables to calculate cooling loads for HVAC system design, which will be particularly valuable in buildings where children are the primary occupants, such as elementary school classrooms and gyms, or daycares.

2. State of the art

Fig. 1 shows the various heat dissipation mechanisms assumed in the steady state heat balance on the human body as defined in [1], and used in numerous studies on human subjects [8,12,13,16,22,23,26]. Though nomenclature[2] varies between sources, the heat dissipation mechanisms generally considered remain the same. The rate of metabolic heat production by an occupant (M, W/m^2), transforms into the net rate of heat generation (H, W/m^2), and rate of external work produced (W, W/m^2) [3,27]. Under an assumption of steady state conditions, H is completely dissipated to the environment through the various mechanisms illustrated on Fig. 1.

As indicated in equation (1), $M-W$ is dissipated to the environment through 2 modes of heat loss: through the skin (q_{sk}, in W/m^2), and through respiration (q_{res}, in W/m^2), Dry heat from the skin is lost through radiation (R, in W/m^2) and convection (C, in W/m^2), while evaporative heat (E_{sk}, in W/m^2) is dissipated from diffusion through the skin (E_{dif}, in W/m^2) and heat loss through sweating (E_{rsw}, in W/m^2). Heat lost from respiration includes evaporative heat (E_{res}, in W/m^2), and dry heat (C_{res}, in W/m^2).

$$\begin{aligned} M-W &= q_{sk}+q_{res}=(C+R+E_{sk})+(C_{res}+E_{res}) \\ &= (C+R+E_{dif}+E_{rsw})+(C_{res}+E_{res}) \end{aligned} \tag{1}$$

2.1. Effect of age: Do children truly generate less "heat" than adults?

There is no consensus in the literature on whether children or adults generate more "metabolic heat" or "net heat" for the same activity. Studies comparing heat generation between children and adults have reached different conclusions based on the purpose of the comparison and the metrics used. From a net heat generation perspective, researchers [2,5,6] who determined and tabulated values in both watts (hereafter H''), and in W/m^2 (H), have consistently found H'' to be significantly lower for children below 12 years old than adult values for similar activities (watching TV, walking, running, etc.). Gao et al. [5] found that girls' H'' significantly increases with age, then reaches stability around 12 to 13 years old (depending on the activity). The same was observed for boys, with H'' increasing with age and reaching stability at around 14 to 16.5 years old. However, Gao et al. [5] also found that H, in W/m^2, was stable with age, with no statistically significant change over the 6 to 69 age range for the same activity. On the other hand, studies seeking to compare thermoregulatory responses found that children have a higher metabolic heat production M than adults when expressed per unit of body mass (W/kg) for the same activity [28].

It is worth noting that net heat generation, internal energy, metabolic heat, and metabolic energy are at times used interchangeably in the literature [29]. As mechanical work (W) is negligible for most sedentary activities [16], conflating H and M in such context is of little consequence. However, in the cases of strenuous exercise inducing sweating, the value of W can be significant, so the differentiation between H and M is nontrivial. For the sake of clarity, net heat (H) will be the metric of interest for the remainder of this paper, with indications of when W can be neglected.

Literature also diverges regarding how the intensity of activities should be compared between children and adults. Most studies [7–12,15,26,30] measure each subject's percentage of their peak oxygen uptake ($VO_{2,\max}$, in mL/kg·min) in a preliminary session and then use it as a means to establish common activity intensity between various individuals who's sweat response they wish to compare. However, Topham et al. [31] demonstrated that when comparing the sweat response of groups with different peak performance (i.e $VO_{2,\max}$), mass (m, in kg), and body surface area (A_D, in m^2), such as children and adults, exercise should be standardized at a fixed H or H'' to avoid the confounding effect of anthropometric and $VO_{2,\max}$ differences on H and sweat response. Notley et al. [29] expanded upon the methodological approaches used to compare thermoregulation between pre-pubertal children and adults by examining how physiological responses are normalized to body size. His statistical analysis showed that using m for ratiometric standardization obscures child–adult differences, likely due to the physiological responses' non-zero y-intercept in relation to m. He concluded that standardizing activities to a fixed H, is necessary to ensure comparable heat loss requirements between children and adults. Furthermore, he confirmed that A_D is a statistically appropriate variable for ratiometric normalization in these comparisons. Consequently, the comparison between the sweat response of children and adults in this paper will be done based on a common value of H.

2.2. Effect of exercise and heat acclimatization

Acclimatization to exercise and/or heat also influence the thermoregulation response of individuals. Wagner [15] tested the thermoregulation and sweat response of subjects of different age groups including pre-pubertal boys, older boys, young men, and older men, before and after undergoing acclimatization, by doing several sessions of exercising in the heat. He found that heat acclimatization improved the thermoregulation and the evaporative cooling of subjects (E, in W/m^2) in all age groups. Despite the improvement, Wagner observed that the young boys and the older men still had lower values of E than the older boys and young men, even after heat acclimatization. Rivera-Brown [32] also tested the effect of exercise and heat acclimatization on the thermoregulatory response of pre-pubertal girls and women. With measured sweat rate ($\dot{m}_{rsw}$, in kg/s·m^2) for girls higher than in any previous study, no significant difference between the $\dot{m}_{rsw}$ of women and the pre-pubertal (PP) girls tested was found. This reaffirms the influence of exercise and heat acclimatization on the thermoregulation and sweating response of individuals, including children, and confirms the importance of including data from such heat and exercise acclimatized children in a general heat balance, as it would reflect a more global and diverse population.

[2] As the general heat balance equation retained for the present paper is that reported 2021 ASHRAE Handbook – Fundamentals [2], the nomenclature adopted is that of this source. Consequently, H in the present paper refers to the net rate of heat generated by an occupant, ie. $M-W$, as adopted by Fanger and other later studies [7,26,32]. It is not to be confused with ISO's use of H for the dry heat loss.

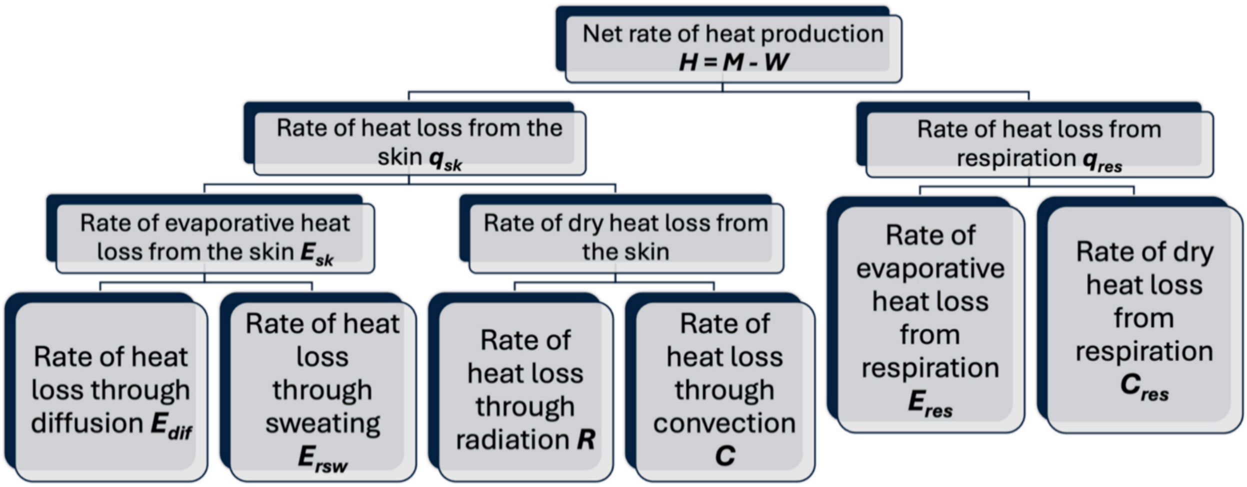

Fig. 1. Steady state heat balance of the human body.

2.3. Measurement of $\dot{m}_{sk}$

The evaporative heat loss from the skin (E_{sk}) of an individual during an activity is calculated based on a measurement of the rate of water loss which evaporated from the skin during exercise ($\dot{m}_{sk}$, in kg/m^2·s). $\dot{m}_{sk}$ can be determined using the mass difference method, where the difference in the subject's mass before (m_{init}) and after the exercise (m_{fin}) is assessed, and corrections are made for fluid intake (m_{fl}), fluid loss through urination (m_u), change in the mass of clothes (m_{cl}) and respiratory water loss (m_{ge}) [33] as expressed in equation (2). $\dot{m}_{sk}$ can be calculated following equation (3) over a duration of time (Δt). Studies [8–11,30,32] that have quantified the difference between the sweat response of children and adults have calculated $\dot{m}_{sk}$ using the mass difference method, but some have neglected to remove m_{ge} and therefore reported a value equivalent to the terms in brackets, in equation (2).

$$m_{sk} = (m_{fin} - m_{init} - m_{fl} - m_u - m_{cl}) - m_{ge} \tag{2}$$

$$\dot{m}_{sk} = \frac{m_{sk}}{A_D \cdot \Delta t} \tag{3}$$

It should be pointed out that $\dot{m}_{sk}$ accounts for all water which has evaporated from the skin, including both regulatory sweat and diffusion of water through the skin, and can be used to calculate E_{sk}. Any additional sweat that has not evaporated whilst on the skin (ie. liquid water remaining in clothing, dripping to the floor or remaining on the skin in its liquid state) would not be included in a thermal balance on the human body as it would not contribute to its heat dissipation.

2.4. Steady state heat balance models

Most heat balance models [1,16,18–23] determine terms C_{res}, R, C, E_{res} through first-principles heat transfer equations. These are somewhat age independent as they can be adjusted to child occupants by inputting accurate values of A_D, M, m, and T_{sk}. In the case of E_{rsw} some of these models calculate it through the product of the heat of vaporization of water (h_{fg}, in J/kg) and the rate of regulatory sweat generation ($\dot{m}_{rsw}$, in kg/(s·m^2)). Having no direct mechanism to quantify the latter, first-principles models usually require some form of iterative process to calculate E_{rsw} and E_{dif} using combinations of the evaporative potential of the environment from a water vapor pressure differential, skin wettedness (w), skin wettedness due to regulatory sweat (w_{rsw}), the maximum water mass which can be held on the skin, and/or sweating efficiency [3,19,24]. In these cases, E_{rsw} and E_{dif} are coupled as diffusion is assumed to occur only on sections of the body not wetted by regulatory sweat (1-w_{rsw}).

The calculation of E_{rsw} and T_{sk} has also been done using empirical equations developed based on experiments performed on adult human subjects [16,34]. Fanger [16] developed a steady state heat balance model that led to a thermal comfort model that is widely used in indoor environments today [35]. In his original work, Fanger [16] made the hypothesis that in order for an occupant to be in a state of thermal comfort, all their net heat production must be lost to their environment (i.e., without any heat being stored in the body), whilst their T_{sk} and E_{rsw} remain confined within specific bounds, depending on the thermal conditions of the environment and a person's activity level. From that perspective, he developed regression models using his own experimental data and that of McNall [36], that relate T_{sk} and E_{rsw} to a person's activity level, expressed as H. Fanger's regression models, along with their coefficient of determination R^2, are shown in equations (4) and (5). In his balance, E_{rsw} and E_{dif} are uncoupled and diffusion is assumed to occur over the entire A_{Du}, not just the areas unwetted by regulatory sweat.

$$T_{sk} = 35.7 - 0.028 \cdot H \qquad R^2 = 68.89\% \tag{4}$$

$$E_{rsw} = 0.42 \cdot (H - 58.15) \qquad R^2 = 53.29\% \tag{5}$$

It is unclear whether Fanger's T_{sk} and E_{rsw} regression models could be used for children. Subjects in Fanger and McNall's experiments were adults over the age of 18, unlikely to reflect children's distinctive thermoregulatory response. Subject's H varied between 58.11 W/m^2 and 153.41 W/m^2 for Fanger's experiment, and H" varied between 175.84 W and 293.07 W in McNall's experiment; a limited range of activity even for children's lower values of H and H". For example, an average 10-year-old boy would generate 425.52 W (372.6 W/m^2) while playing basketball, a common activity that would induce sweating even in conditions of thermal comfort.[3] Additionally, as Fanger's regressions considered the lower end of mild environments (15.56 to 22.22 °C), the influence of T_{db} on T_{sk} and E_{rsw} was judged to be negligible. As the regressions have since been adopted and used in environments that are not strictly mild ((−20 to 40 °C) in [21], (−35 to 10 °C) in [18]) and/or do not guarantee thermal comfort [21,35], this assumption should be verified if a model is to be used broadly for *SHR* estimation purposes.

Though various steady state one-node heat balance models exist in the literature, all those found rely on Fanger's regressions to express E_{rsw} and none has seen their applicability to children in indoor environments validated sufficiently to provide the *SHR* pursued. Some studies have

[3] Calculations were done based on metabolic data from the Youth Compendium [6] and anthropometric data (height and mass) of the 50th percentile 10-year-old boy [56,57].

explored the effect of age on the thermoregulatory system and developed heat balance models for the elderly to account for their unique thermoregulation [37]. No such models were found for children. Rather, various authors have attempted to adjust existing adult models to the specificities of children. Cheng et al. [21] partially altered the Comfort Formula (COMFA) energy budget to account for child-specific data, creating COMFA-kid. Their calculation of E_{rsw} uses Fanger's adult regression with the assumptions that a child's E_{rsw} will be half, regardless of age. No basis was provided for this assumption, which should be investigated. Additionally, their model does not distinguish between C_{res} and E_{res}, making it's use impossible to calculate *SHR*. McCullough et al. [22] and Schlabach et al. [23] applied a steady state heat balance to the child subjects in their research on temperature ratings for children's cold weather clothing and sleeping bags. They used child-specific data, particularly H and A_D, in most heat dissipation terms but used an equation for E_{sk} which only applies to a person who is not actively sweating.

It is our premise that terms C_{res}, R, C, and E_{res} in equation (1), as calculated in [2] through first-principles equations that can be altered to account for age-dependent variables, can therefore be used to calculate heat loads from children. Despite the data limitations of Fanger's regression models, we posit it is possible to use the same hypotheses to build a new regression model expressing T_{sk} and E_{rsw} from H for child occupants. As a number of studies have analyzed and compared the thermoregulation and sweating response of children and adults [7–12,15,21,26,30], data collected from these studies can be used to build these new child-specific regression models.

3. Methodology

In order to develop a complete child-specific steady-state heat balance model, two main steps were undertaken. First, the first principles equations found in [3] for M, $R + C$, C_{res} and E_{res} were modified to account for children's unique characteristics and calculated for the considered activities in Section 3.1. They result in equations (6) through (14) presented in Section 3.1. Second, a child-specific regression model expressing E_{rsw} as a function of H and the dry bulb temperature (T_{db}, in °C) was built from experimental data from the literature. This was done by 1) finding experimental studies that measured and reported the physiological characteristics of child subjects, as well as environmental conditions, T_{sk}, $\dot{m}_{sk}$, and oxygen consumption (VO_2) during exercise; 2) post processing the data from said studies to obtain values of T_{sk}, E_{rsw}, H, Age, and T_{db}; and 3) building regression models based on this data that express E_{rsw} as a function of H and T_{db}. This second step is detailed further in Sections 3.2 to 3.4 below.

3.1. Modified equations in the heat balance model

Equations (6) to (14) are modified steady state equations for M, $R + C$, C_{res}, and E_{res} as reported in [1,38]. In equation (5), the basal metabolic rate (*BMR*, in W) is calculated using the Schofield equations which were developed based on measurements of children, with validated equations for boys and girls, aged 3 to 18 years old [39]. MET_y is derived from the Youth Compendium of Physical Activity [6], which is based on measurements of energy expenditure of children aged 6 to 18 years old.

$$M = \frac{BMR \cdot MET_y}{A_D} \tag{6}$$

Equation (7) expresses the total radiative and convective heat loss from the skin. In the results, we will examine if T_{sk} is an age dependent variable. Al-Rashidi [40] proved experimentally that the existing data on clothing thermal resistance R_{cl} and clothing factor f_{cl} for adults in common references [38] can be used for children. h is the combined heat transfer coefficient of convection (h_c) and radiation (h_r). Table 6 in [1] provides values of h_c corresponding to various conditions of occupancy. Viswanathanet al. [41] showed the impact of an adult's height and mass on h_c is insignificant. It can therefore be assumed that using adult values of h_c for children would be inconsequential. No studies were found that measured nor calculated h_r for child subjects, therefore, adult values of h will be used. T_o is the operative temperature in the environment, defined as the average between the mean radiant temperature (*MRT*) and the ambient air temperature (T_{db}), and weighted by h_r and h_c respectively [1].

$$R + C = \frac{T_{sk} - T_o}{R_{cl} + \frac{1}{f_{cl} \cdot h}} \tag{7}$$

First order thermodynamic equations for the convective and evaporative heat loss in the respiratory tract can respectively be seen in equations (8) and (9), using the the respiration rate per A_D ($\dot{m}_{res}$, in kg/m^2·s), the specific heat of the expired air ($c_{p,a}$, in J/kg·K), the dry bulb temperature of the expired air (T_{ex}, in °C), the heat of vaporization of water in the expired air ($h_{fg,re}$, in J/kg), the absolute humidity of the expired air (W_{ex} in kg$_{wv}$/kg$_{da}$), and the absolute humidity of the inspired air (W_a, in kg$_{wv}$/kg$_{da}$).

$$C_{res} = \dot{m}_{res} \cdot c_{p,a} \cdot (T_{ex} - T_{db}) \tag{8}$$

$$E_{res} = \dot{m}_{res} \cdot h_{fg,re} \cdot (W_{ex} - W_a) \tag{9}$$

As no relationship was found that was specifically validated for children, $\dot{m}_{res}$ is approximated as a function of M following equation (10) from [42]. Given the small values of C_{res} and E_{res} in comparison to the other terms in the heat balance, the dependence of $\dot{m}_{res}$ on an age-appropriate value of M is deemed adequate for this application.

$$\dot{m}_{res} = 1.43 \cdot 10^{-6} \cdot M \tag{10}$$

W_{ex} can be expressed as a function of the partial pressure of water vapor in the inspired air (p_a, kPa) and W_a as seen in equation (11), and T_{ex} as a function of T_a and W_a as seen in equation (12) [42].

$$W_{ex} = W_a + 0.029 - 0.00495 \cdot p_a \tag{11}$$

$$T_{ex} = 32.6 + 0.066 \cdot T_a + 32 \cdot W_a \tag{12}$$

In order to avoid coupling E_{rsw} and E_{dif} through calculations of w_{rsw}, equations proposed in [3] for E_{dif} cannot be used. Instead, Fanger's assumption that there is diffusion all over over the body is used in conjuncture with $\dot{m}_{sk}$. Thus E_{dif} can be calculated using equation (13), proposed by [16], where m_p represents the skin permeance in the epidermal layer, taken as 4.578×10^{-3} kg/hr·m^2·kPa [16] and p_a is the vapor pressure at the ambient pressure, in kPa. Stamatas et al. [43] have found that although young children have a more permeable skin than adults, that difference is no longer significant after the age of 6. Additionally, the saturated vapor pressure at skin temperature ($p_{sk,s}$, in kPa) can be approximated using equation (14) from thermodynamic tables. This calculation of E_{dif} follows Fanger's hypothesis of assuming diffusion all over the body, an acceptable assumption considering a distinction between E_{dif} and E_{rsw} is unnecessary for calculating the *SHR*.

$$E_{dif} = h_{fg,sk} \cdot m_p \cdot (p_{sk,s} - p_a) \tag{13}$$

$$p_{sk,s} = 0.256 \cdot T_{sk} - 3.372 \tag{14}$$

3.2. Data selection

Publications likely to contain the experimental data sought to establish a regression for E_{rsw} explore topics of sweating, heat and exercise tolerance, and thermoregulation of children of different ages, often in comparison to adults, under varying activity levels and ambient conditions. Keywords used for the collection of relevant literature include: "thermoregulation", "skin temperature", "sweating", "heat loss", "metabolic heat generation", "sudomotor" and their synonyms, accompanied with the terms "children", "pediatric", "boys", and "girls". Search for pertinent literature was performed using various search engines: SCOPUS, Compendex, Science Direct, Google Scholar, Pubmed and the university library search engine. The resultant database included 162 studies, but was reduced to 10 publications after excluding topics such as unhealthy children, specific diseases impacting sweat rates, children below 3 years old, and studies that did not provide at least one of the fundamental data required to build the regressions, namely VO_2, T_{db}, RH, and $\dot{m}_{sk}$ (or E or E_{sk}). Details of the literature retained for analysis are listed in Table 1.

Subject physiological data was extracted, namely age, gender, height, mass, A_D, and maximal oxygen uptake ($VO_{2,\max}$). Experimental conditions extracted were $T_{db,}$ RH, length of experiment (Δt), details of the exercise protocol (such as the length of exercise/rest periods), and exercise intensity expressed in $\%VO_{2,\max}$. Experimental results extracted were the steady state values of T_{sk} and $\dot{m}_{sk}$, if steady state had been reached.

Steady state was judged to have been reached depending on the intensity of the exercise expressed in VO_2. ISO 8896 [44] suggests that if VO_2 reaches a steady state at a value below 60 l/h, the partial method can be used for the calculation of M from measurements of VO_2, at the end of the exercise period. If VO_2 is above 60 l/h, ISO 8896 suggests that steady state will not be reached for VO_2 as it is above the maximal aerobic capacity, and therefore steady state will equally not be reached for M. In this case, the integral method should be used, and measurements of VO_2 need to include the rest period after the exercise to account for any oxygen debt. For most of the considered studies, it is unclear if a specific standard was followed in their measurements of VO_2; measured values of VO_2 were not reported nor the moment when said measurements occurred. Mostly, studies used VO_2 measurements to confirm the prescribed $\%VO_{2,\max}$ of the exercise was respected. Additionally, none of the papers where the VO_2 measurements exceeded 60 l/h specified if they included the rest period in their reported values. Considering these limitations, the reported measurement of VO_2 in each study was used to calculate M using the partial method described by ISO8896 [44]. Some papers provided experimental results of $\dot{m}_{sk}$ (or E) for 2 exercise bouts separated by a rest period. For these cases (Drinkwater et al. [9], Meyer et al. [11], Falk et al. [10]), the values at the end of the last exercise bout were taken, when the core temperature T_{cr} measurements indicated that steady state had been reached.

3.3. Data post processing

Some of the data required to construct the regression models, namely A_D, H, $T_{wb,}$ and E_{rsw}, were not explicitly provided in the reviewed literature and had to be calculated from other extracted values. The protocol used for these calculations is as follows.

3.3.1. Wet bulb temperature (T_{wb})

When T_{wb} was not reported, T_{db} and RH were used to generate it. T_{wb} was determined from T_{db} and RH using the psychrometric chart [45]. This has the benefit of accounting for the effect of air humidity on the sweating response of the subjects, while simultaneously limiting the number of dependent variables in the regression models. T_{db} and RH were also used to obtain W_a.

3.3.2. Body surface area (A_D)

When neither individual values of the subjects nor a mean for each subgroup were reported, the mean A_D was estimated based on the reported mean mass (w, in kg) and height (l, in m) of the subjects following equation (15) by DuBois [46].

$$A_D = w^{0.425} \cdot l^{0.725} \cdot 0.007184 \tag{15}$$

3.3.3. H

M for a given activity can be calculated based on the measured value of VO_2 during the activity. Various methods exist, most notably the Weir method [47], the ISO 8896 method [44], and the ASTM method [48]. Then, H for that activity can be calculated by subtracting the mechanical work per A_D, W, dispensed on the activity from M. Methods used to determine the value of M associated with a physical activity based on measurements of VO_2 vary across the considered studies. Leites [26] and Arlegui [13] used the method described by Weir [47] to calculate M. Others (Inbar [8], Davies [7], Delamarche [12], Wagner [15], Shibasaki [30]) did not specify how they calculated M based on VO_2 measurements, while others (Drinkwater[9], Falk [10], Meyer [11]) did not calculate M at all. To maintain a consistent methodology for all data points, we used the method detailed in ISO 8996 [44] to determine M of subjects through equations (16) and (17) using their measured oxygen uptake VO_2, m, the energetic equivalent (EE, in W·h/l O2) and their calculated A_D, assuming a respiratory quotient RQ of 0.85.

$$EE = (0.23 \cdot RQ + 0.77) \cdot 5.88 \tag{16}$$

$$M = \frac{EE \cdot VO_2 \cdot m}{A_D} \tag{17}$$

Some of the studies comparing thermoregulation of children and adults (Inbar et al. [8], Leites et al. [26]) measured and reported the workload of the performed exercise W, expressed in W/m^2, was deducted from M to obtain H, as expressed in equation (18). If W was not reported and no exercise details were provided for its calculation, a value of zero was assumed.

$$H = M - W \tag{18}$$

Table 1
Details of the studies used in building the regression model.

Author	Year	Country	T_{db} (°C), RH (%)	Exercise protocol	Length of experiment
Inbar et al.	2004	Israel	41 °C, 21 %	Cycle ergonometer	85 min
Davies	1981	England	21 °C, 50 %	Treadmill	60 min
Leites et al.	2016	Canada	35 °C, 35 %	Cycling	115 min
Drinkwater et al.	1977	United States	28 °C, 45 %	Treadmill	100 min
			35 °C, 65 %		
			48 °C, 10 %		
Falk et al.	1991	Canada	42 °C, 20 %	Cycle Ergonometer	50 min
Meyer et al.	2007	Brazil	41 °C, 19 %	Cycling	60 min
Delamarche et al.	1989	France	45 °C, 20 %	Cycle Ergonometer	60 min
Wagner et al.	1972	United States	49 °C, 17 %	Treadmill	40–90 min
			22 °C, 28 %		60 min
Shibasaki et al.	1997	Japan	30 °C, 45 %	Cycle Ergonometer	45 min
Chen et al.	2024	China	25 °C, 55 %	Sitting down	45 min

3.3.4. E_{rsw}

E_{rsw} was not reported and had to be calculated from water mass balance or from other latent heat dissipation mecanisms. The method used varied according to the data available. Most studies [4,8,11,12,15,30] determined the values of $\dot{m}_{sk}$ following equation (2) for participants performing specific physical activities at intensities documented through VO_2 (or $\%VO_{2,\max}$). E_{sk} was then calculated from $\dot{m}_{sk}$ and $h_{fg,sk}$ through equation (19). $h_{fg,sk}$ as well as the specific volume of water v_f used in the conversion of $\dot{m}_{sk}$ from mL/min·m^2 to kg/s·m^2 were taken at the reported T_{sk} using psychometric charts. As T_{sk} was not reported by Meyer [11], it was approximated from Inbar [7] and Drinkwater [8] where subjects of similar age and gender performed

Table 2
Subject characteristics (Age, gender), environmental conditions (T_{db}, RH wind speed), and Physiological Measurements (H, T_{sk}, E_{rsw}) from post-processed study data**.

Author	v_a (m/s)	Gender	Age	T_{db} (°C)	T_{sk} (°C)	RH (%)	H (W/m^2)	E_{rsw} (W/m^2)
Inbar et al. (2004)	< 0.3	Boys	9.4	41	37.47	21	215.59	185.17
		Men	22.7	41	38.02	21	299.24	255.21
		Men	71.0	41	37.40	21	159.05	194.47
Davies et al. (1981)	2–4	Boys	12.9	21	30.85	50	477.36	132.13
		Girls	13.8	21	31.80	50	429.50	126.80
		Men	36.1	21	28.12	50	592.08	275.01
Leites et al. (2016)	NR	Boys	11.5	35	36.25	35	180.41	137.22
		Men	**22.9**	**35**	**36.11**	**35**	**211.16**	**177.82**
		Men	22.9	35	35.85	35	125.38	97.13
Drinkwater et al. (1977)	< 0.84	Girls	12.0	28	33.51	45	137.31	76.29
		Girls	12.0	35	35.65	65	137.31	182.76
		Women	20.6	28	33.0	45	204.33	90.91
		Women	**20.6**	**35**	**35.2**	**65**	**204.33**	**186.58**
		Women	20.6	48	37.2	10	204.33	359.47
Falk et al. (1991)	< 0.2	Boys	10.8	42	36.1	20	272.06	198.18
		Boys	13.6	42	36.3	20	314.20	233.56
		Boys	16.2	42	36.9	20	370.23	242.48
Meyer et al. (2007)	NR	**Girls**	**10.5**	**41**	**35.64**	**19**	**214.53**	**155.95**
		Boys	**9.9**	**41**	**37.23**	**19**	**238.01**	**174.33**
		Women	21.5	41	35.18	19	262.70	244.50
		Men	23.4	41	37.18	19	331.08	306.16
P. Delamarche et al. (1989)	0.8	Boys	10.5	45	37.0	20	51.40	172.82
		Boys	10.5	45	37.0	20	55.60	166.64
	2	Boys	10.5	20	31.6	20	346.80	91.68
		Boys	10.5	20	31.6	20	314.19	106.99
Wagner et al. (1972)	NR	Boys	12.5	49	38.15	17	194.20	304.89
		Boys	12.5	49	37.05	17	195.00	353.69
		Boys	15.5	49	37.90	17	235.00	377.41
		Boys	15.5	49	36.80	17	216.00	397.51
		Men	27.5	49	37.85	17	219.00	363.50
		Men	27.5	49	36.55	17	207.00	389.29
	0.92	Men	24.5	49	37.40	17	213.00	385.24
		Men	24.5	49	36.05	17	211.00	446.41
		Men	56.5	49	37.75	17	222.13	335.37
		Men	56.5	49	36.62	17	221.00	373.32
	NR	Boys	12.5	22	30.40	28	187.00	44.35
		Boys	12.5	22	30.40	28	195.00	45.65
		Boys	15.5	22	31.30	28	235.00	66.45
		Boys	15.5	22	30.60	28	216.00	57.66
		Men	27.5	22	29.50	28	208.00	86.21
		Men	27.5	22	30.20	28	201.00	54.28
Shibasaki et al. (1997)	NR	Boys	10.9	30	33.7	45	206.70	138.05
		Men	22.9	30	34.5	45	275.00	194.51
Chen et al. (2024)	< 0.05	Adults	38.6	25	32.78	55	50.10	0.00
		Children	7.3	25	33.15	55	69.60	0.00
Fanger (1976)	NR	Adults	NR	NR	NL	45	58.15	NR*
				22.22	NL	45	90.71	NR*
				18.89	NL	45	120.95	NR*
				15.56	NL	45	153.52	NR*
McNall (1967)	0.1 – 1.15	Adults	NR	18.88, 22.22, 25.56	NR	25, 45, 65 (NL)	175.84**	NR*
				15.55, 18.88, 22.22,			234.46**	NR*
				12.22, 15.55, 18.88			293.07**	NR*

**NR refers to a measured value that was not reported. Age is not explicitly specified in the Fanger study, only that the subjects were "college aged". NR* refers to Fanger and McNall's lack of reporting of E_{rsw} (only E was reported). NL refers to the lack of linkage between E and coincident values of T_{db}.and RH. The values marked ** represent H" expressed in W not H in W/m^2.

activities at similar intensity levels. This was deemed acceptable as the narrow range of T_{sk} (29.5 °C to 38.15 °C) in all considered studies in Table 1 resulted in a minimal impact on $h_{fg,sk}$ (18.59 kJ/kg) and a maximum difference in E_{sk} of 1.12 W.

$$E_{sk} = \dot{m}_{sk} \cdot h_{fg,sk} \quad (19)$$

Special attention was put into the mass water loss method and whether the respiratory water loss (m_{ge}) was accounted for in the calculation of $\dot{m}_{sk}$ through the mass difference method (Equation (2) and (3). When it was not, the reported value was used to calculate the overall evaporative heat loss E, not E_{sk}. In those cases, E_{sk} was calculated using equation (20).

$$E_{sk} = E - E_{res} \quad (20)$$

It should be noted that in estimating the cooling effects of E_{sk} on the body from $\dot{m}_{sk}$ measurements, it is assumed that all sweat has evaporated whilst on the skin (ie. regulatory sweat), thus excluding any sweat that accumulates on the skin or drips. Shibasaki [30] reported that no sweat was observed to drip from the subjects' bodies during the experiments. However, most of the studies considered did not explicitely mention whether sweat was observed dripping from the body or not. Some studies [9,26] dried the subjects bodies before the final mass measurement, demonstrating an awareness of excluding non-evaporated sweat from the calculation of $\dot{m}_{sk}$. Since $\dot{m}_{sk}$ was explicitly used for evaporative heat loss calculations in [10,12,15], it can be inferred that the researchers distinguished between evaporated sweat (ie. regulatory sweat) and sweat that dripped off or remained on the body after the exercice was completed.

Two studies did not measure nor report $\dot{m}_{sk}$. Leites [26] calculated E_{sk} for specific physical activities at exercise intensities expressed in % $VO_{2,\max}$ by measuring M, W, R, C, C_{res}, and E_{res}, then calculated E_{sk} using the steady state heat balance as seen in equation (1). Davies [7] calculated E following equation (1) by measuring M, W, R, C, C_{res}, and E_{res}. Their reported values of E_{sk} and E were used in subsequent calculations.

The value of E_{rsw} was calculated using equations 21 or 22, depending on whether values of E or E_{sk} could be calculated from the paper's data.

$$E_{rsw} = E - E_{dif} - E_{res} \quad (21)$$

$$E_{rsw} = E_{sk} - E_{dif} \quad (22)$$

3.4. Statistical analysis

One-way analysis of variance (ANOVA), Pearson correlation, and standardized regression analysis were used to analyze the individual effect of age, H, T_{db}, W_a, and T_{wb} on both E_{rsw} and T_{sk} using Minitab statistical software. The first regression model was built for E_{rsw} as a function of H, T_{wb}, and *Age*, and a second regression model was built as a function of H, T_{db}, W_a, and *Age* based on the post processed data from the literature. Statistical significance was accepted at $p < 0.05$.

4. Results and analysis

4.1. Post-processed data

The subject physiological characteristics (*Age*, gender), experimental conditions (T_{db}, W_a, wind speed), and the post processed experimental results (H, T_{sk}, E_{rsw}) of the considered child inclusive studies, are presented in Table 2. Measurements that were not reported are listed as 'NR'. In the table are also listed Fanger and McNall's experimental results on adult subjects, as extracted from Fanger's graphs on T_{sk} and E as a function of H. T_{wb} in the child inclusive studies varied from 12 °C to 29.13 °C and T_{db} varied from 20 °C to 49 °C. McNall's sweat rate experiments, which constituted most of the data points in Fanger's E vs H graph, covered a range of T_{wb} from 4.64 °C to 20.73 °C, and activity levels corresponding to 175.84 W, 234.46 W, and 293.07 W.

Fanger and McNall's data lacks linkage (NL) between individual measurements of H and E and the specific environmental conditions (T_{wb}, T_{db} or W_a) under which they were measured. This made it difficult to compare the sweat response between children and the adults in McNall's study at the same H and T_{wb}. This also made it impossible to calculate the E_{rsw} values for Fanger and McNall's data points through equation (21), as T_{wb} is necessary for the calculation of E_{res} and E_{dif}. Consequently, the measured values of E_{rsw} in Fanger and McNall's studies were not reported (NR*). The same applies to Fanger's T_{sk} vs H graph where the association between individual values of H and T_{wb} was not provided. These limitations in Fanger and McNall's data prevented their inclusion in the analysis of child–adult sweating response and skin temperature differences.

4.2. Data analysis

4.2.1. E and E_{rsw}

Fig. 2 and Fig. 5 show the post processed values E and T_{sk} for children and adults as a function of H. The data points are colored depending on the value of T_{db} during the measurement. T_{db} is used to illustrate the effect of the environmental conditions on E and T_{sk}, but the individual effects of T_{db}, T_{wb} and W_a on E and T_{sk} will be analyzed separately. E values from Fanger are included as blank squares, as the associated T_{db} values are unknown.

It is clear from Fig. 2 that even at low values of H, E is highest at the highest values of T_{db}, indicating its strong influence on E. At low values of T_{db} (colored in yellow), a high H is required to induce a high E in both children and adults, implying the influence of H on E. It is also worth noting that the points circled in a dashed line correspond to measurements where T_{db} is higher than 45 °C, which is significantly higher than the core temperature of the human body. In these circumstances, E is high even at a low H level to compensate for the body's inability to lose heat through $R + C$, as the temperature difference is causing a sensible heat gain from the environment.

Certain points were selected for direct child/adult comparison of E. The circled data points annotated with * correspond to children (PP) from the Falk study [10] at T_{db} of 42 °C and RH of 20 % (dark blue circle), adults from the Shibasaki [30] study at T_{db} of 30 °C and a RH of 21 % (green square), and adults from the Meyer [11] study at T_{db} of 41 °C and a RH of 19 % (dark blue square), where adult and child subjects have similar values of H (in grey in Table 2). These three points show that at a similar H and environmental conditions, the adults had a higher value of E than the children ($\Delta E = 46.32$ W/m^2). It also shows

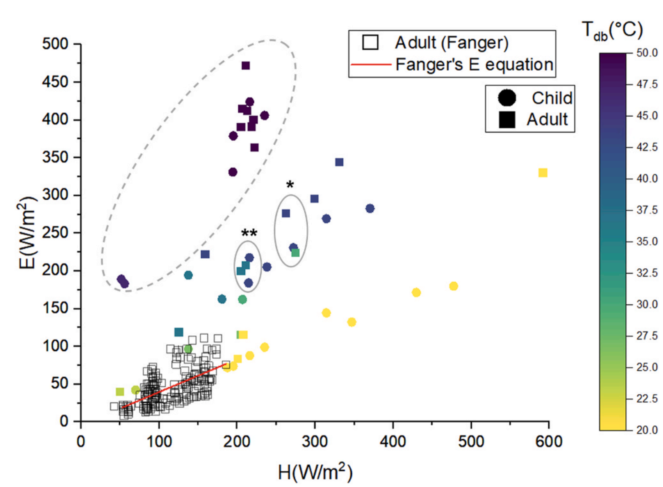

Fig. 2. measured values of E as a function of H, colored by the T_{db} of the measurement.

that a significantly higher T_{db} is needed for children to have a similar value of E to adults, at the same activity level. Points annotated with ** correspond to 2 children measurements from the Meyer [11] study at T_{db} of 41 °C and a RH of 19 % (dark blue circles), one adult measurement from the Drinkwater [9] paper (T_{db} of 35 °C and a RH of 65 %) and one adult measurement from the Leites [26] paper (T_{db} of 35 °C and a RH of 35 %) (teal squares). These point pairs (in bold in Table 2) also show that for children to have a similar value of E to adults, they need to exist in a hotter environment (higher T_{db}). However, the RH in the adults measurements were higher than in the children measurements, so the effect of RH will be examined in the coming section, as well as the feasibility of using T_{wb} to combine the effects of T_{db} and RH.

Fig. 3 shows the measured values of E_{rsw} of children and adults in the considered literature, alongside the predictions of Fanger and COMFA-kid. It is clear that neither Fanger's adult regression nor the altered COMFA-kid regression accurately predict the measured values in environmental conditions beyond 22.5 °C. This is worth noting, as COMFA-kid's validation has been conducted in outdoor conditions where T_{db} reached 40 °C. Even in mild environments (points in dark blue and indigo), COMFA-kid underestimates E_{rsw} across the range of H (200 to 500 W/m^2) to be expected for children performing sports in a school gymnasium, while Fanger's adult regression oversestimates it.

In order to analyze the effect of various factors on E_{rsw} and T_{sk}, the data was grouped by 5 input variables: 4 quantitative variables (T_{wb}, T_{db}, W_a and H), and one categorical variable (*Age*). Three *Age* categorizations were considered: Age categorization 1 identified subjects as a 'children' when younger than 18 years old and 'adults' otherwise; Age categorization 2 identified subjects as either 'pre-pubertal' (PP) or 'not prepubertal' (nPP), and Age categorization 3 which identified subjects as either PP or 'adults', therefore removing all subjects belonging to the intermediate age categories from the analysis (i.e. pubertal children, late pubertal children, and the elderly were excluded). The criterion for identification as PP relied on maturation stage tests conducted within the studies analyzed.

One way ANOVA tests revealed that *Age* had no statistically significant effect on T_{sk}, whether through Age categorizations 1, 2, or 3, while all 3 age categorizations demonstrated a significant effect on E_{rsw} (p values 0.04, 0.025, and 0.012, respectively). The results of a Pearson correlation test between the input variables T_{wb}, T_{db}, H, and W_a and the output variables E_{rsw} and T_{sk} are shown in Table 3. It can be seen that among the environmental variables, T_{db} has the strongest correlation with E_{rsw} and T_{sk}, and that H has a weak and moderate correlation respectively. Past research on adult subjects has also found T_{db} had a greater influence than H on T_{sk}, even in mild environmental conditions [49].

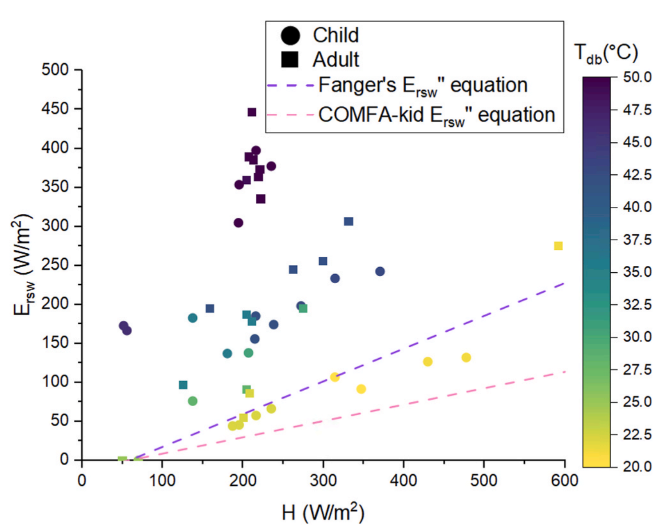

Fig. 3. measured values of E_{rsw} as a function of H, colored by the T_{db} of the measurement, contrasted to the Fanger and COMFA-kid regressions.

Table 3
Pearson correlation test results.

	E_{rsw}	T_{sk}
T_{wb}	0.695 (strong)	0.890 (very strong)
T_{db}	0.835 (very strong)	0.922 (very strong)
H	0.231 (weak)	− 0.312 (moderate)
W_a	0.379 (moderate)	0.578 (strong)

When the same test was performed on the adult data in Fanger and McNall's studies, a strong correlation was found between H and E (0.62) and a strong negative correlation was found between H and T_{sk} (−0.793). The probable reason is that the mild environmental temperatures in Fanger and McNall's studies allowed for a strong correlation between H and T_{sk} and E, while the extremely hot and dry environmental temperatures in the child inclusive literature overshadowed the influence of H on T_{sk} and E. It is not possible to analyze the effect of T_{wb}, T_{db}, or W_a on E or T_{sk} in Fanger's results due to the lack of linkage between the data points and their environmental conditions.

A standardized regression analysis alongside a Pareto test was conducted to determine which environmental variables (T_{db}, T_{wb}, W_a) should be included in a regression model of E_{rsw} and T_{sk}, and to assess whether *Age* influences E_{rsw} and T_{sk}. The analysis was done using W_a (in kg$_{wv}$/kg$_{da}$) in place of RH to ensure variable independence. 4 regression models to predict E_{rsw} and T_{sk} were examined: *A)* as a function of T_{db}, W_a, H, and Age categorization 1; *B)* as a function of T_{wb}, H, and Age categorization 1; *C)* as a function of T_{db}, W_a, H, and Age categorization 3; and *D)* as a function of T_{wb}, H, and Age categorization 3. The results for the E_{rsw} regressions are presented in Fig. 4.

Age categorizations 1 and 3 have a significant effect in regressions *A* and *C* but not in *B* and *D*, signifying the strength of the earlier regressions. In regressions *A* and *C*, T_{db} has the highest effect on E_{rsw}, while W_a's effect is insignificant. Coupled with the fact that regressions *A* and *C* are more robust (higher R^2 and R^2_adj) than *B* and *D*, it can be concluded that a regression with T_{db} expressing the environmental influence is the most efficient. Knowing the regression is intended to assess *SHR* of children in mechanically conditioned indoor environments, conditions considered should extent beyond the strict bounds of Fanger's tests (15.86——22.22 °C). Recent research indicates indoor temperature setpoints based on comfort conditions are often found to be higher than 23 °C in summertime [50,51], reaching 26 °C [49,52], at times reaching values of 27–30 °C [53–55]. This is especially true for heat acclimatized people living in warmer climates who are more comfortable at the higher end of what are considered 'mild' temperatures [35]. This reaffirms the importance of including T_{db} in a regression predicting E_{rsw} for cooling load calculation purposes as it must function in all conditions likely to occur indoors in mechanically ventilated spaces. Although Fanger's E_{rsw} regression was designed for adults in mild conditions, it continues to be used beyond these limits in various applications, raising questions about its appropriateness. The regression has been incorporated into adaptive heat balance and physiological models [18,21,35], as well as building energy simulation software like EnergyPlus [25]. However, given that the regression does not account for factors such as children's distinct sweating responses or the effects of temperatures outside its limited range, its continued use in such contexts warrants further scrutiny.

4.2.2. T_{sk}

Fig. 5 shows the measured values of T_{sk} in the child inclusive literature colored by the T_{db} of the measurement, as well as Fanger's measurements and T_{sk} equation results.

Fig. 5 shows Fanger's measurements have a much lower range of H and T_{sk} than the child inclusive literature. Within that range of H and T_{db}, his regression performs well, but as T_{db} increases, T_{sk} becomes a

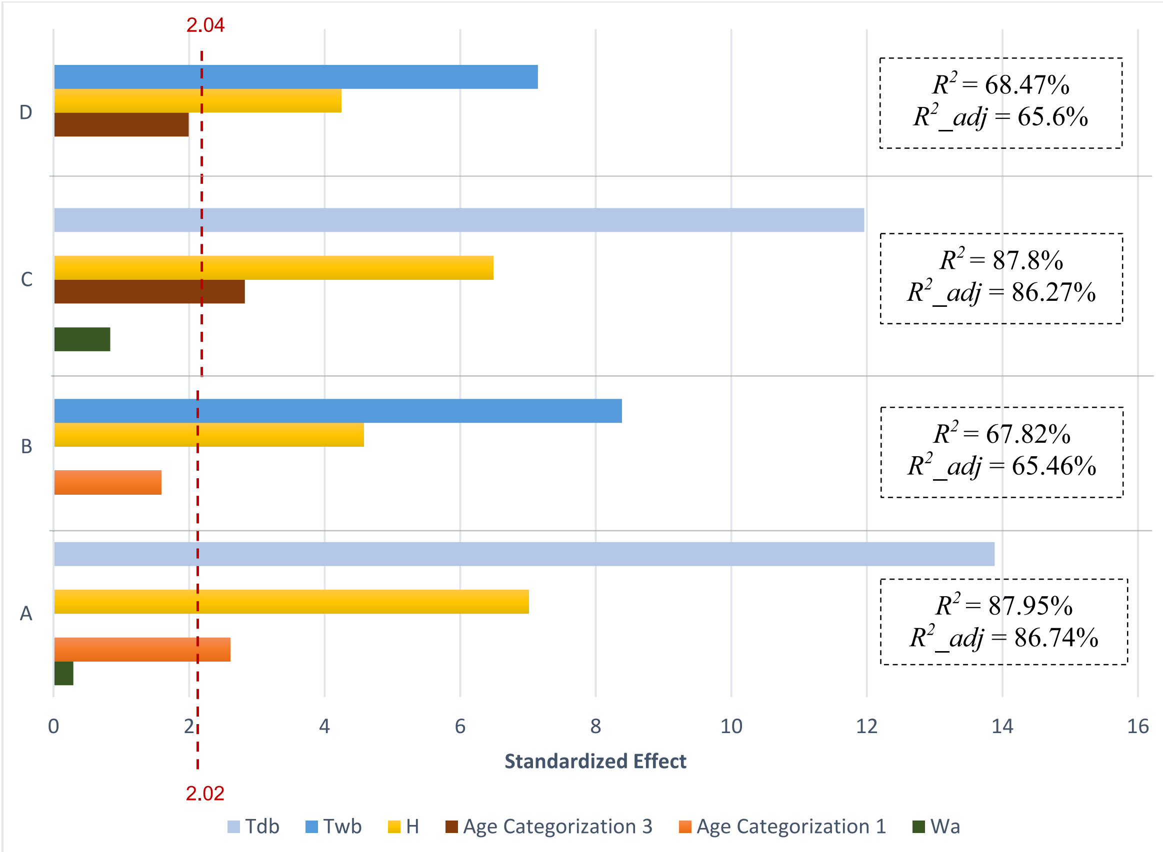

Fig. 4. Pareto Chart of standardized effects of E_{rsw}. $\alpha = 0.05$.

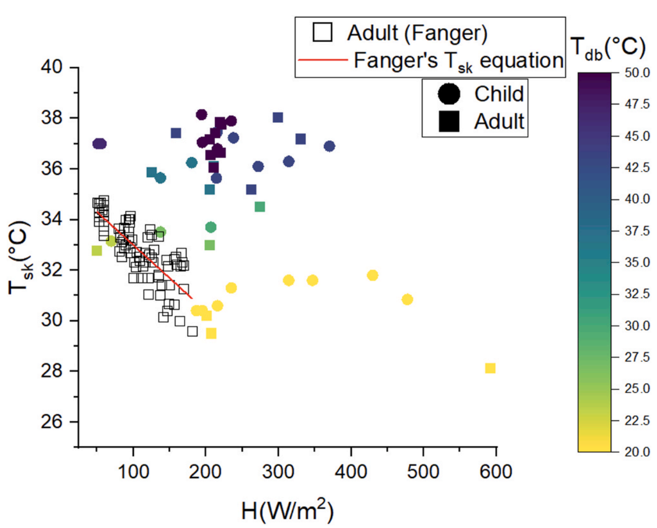

Fig. 5. measured values of T_{sk} as a function of H, colored by the T_{db} of the measurement.

function of T_{db} and H seems to no longer have an influence. This was also observed in the PHS regression model, where H was not a significant factor for unclothed subjects in hot environments and was less influential than environmental conditions for clothed subjects [17]. Though some of the child-specific data included in the analysis can be said to have been obtained in extremely hot environments, some milder values (30 °C to 37 °C) are still likely to be encountered in unconditioned buildings. In colder temperatures, even as H increases, T_{sk} plateaus at a value of ~ 30 °C, which reaffirms Fanger's hypothesis that his regression of T_{sk} is bound in a specific range. Similarly, regardless of the values of T_{db}, documented values of T_{sk} are limited between a minimum of 28.12 °C and a maximum of 38.1 °C. Finally, no clear adult/child differences can be seen in Fig. 5, and an ANOVA test revealed that none of the 3 earlier age categorizations had a significant influence on T_{sk}. The Pearson correlation test results in Table 3 show that T_{sk} has the highest correlation with T_{db}, while the correlation with H is moderate.

Fig. 6 demonstrates that only T_{db} and T_{wb} have a significant effect on T_{sk} in any regression. Based on these results, it can be concluded that age has no significant influence on T_{sk}, and therefore Fanger's regression can be used to predict children's T_{sk} within his range of T_{db} and H. As established in past literature [17], a T_{sk} regression should be used as a function of T_{db} for more thermally stressful environments.

4.3. Regression models for E_{rsw}

As both age categorizations 1 and 3 were found to be influential on E_{rsw}, two regressions were developed: one for children (age 18 years old and below), and one for PP children. Equations (23) and (24) represent the regression models of E_{rsw} built for children using age categorization 1 and 3, respectively. The "child regression model" (equation (23) has an R^2 of 83.88 % and an R^2_adj of 82.42 %, and the "PP regression model" (equation (24) has an R^2 of 79.78 % and an R^2_adj of 77.09 %. Both these regressions models have a noticeably higher R^2 than the Fanger E_{rsw} regression model ($R^2 = 53.29$ %).

$$E_{rsw} = -232.5 + 9.16 \cdot T_{db} + 0.3722 \cdot H \quad (23)$$

$$E_{rsw} = -209 + 7.676 \cdot T_{db} + 0.335 \cdot H \quad (24)$$

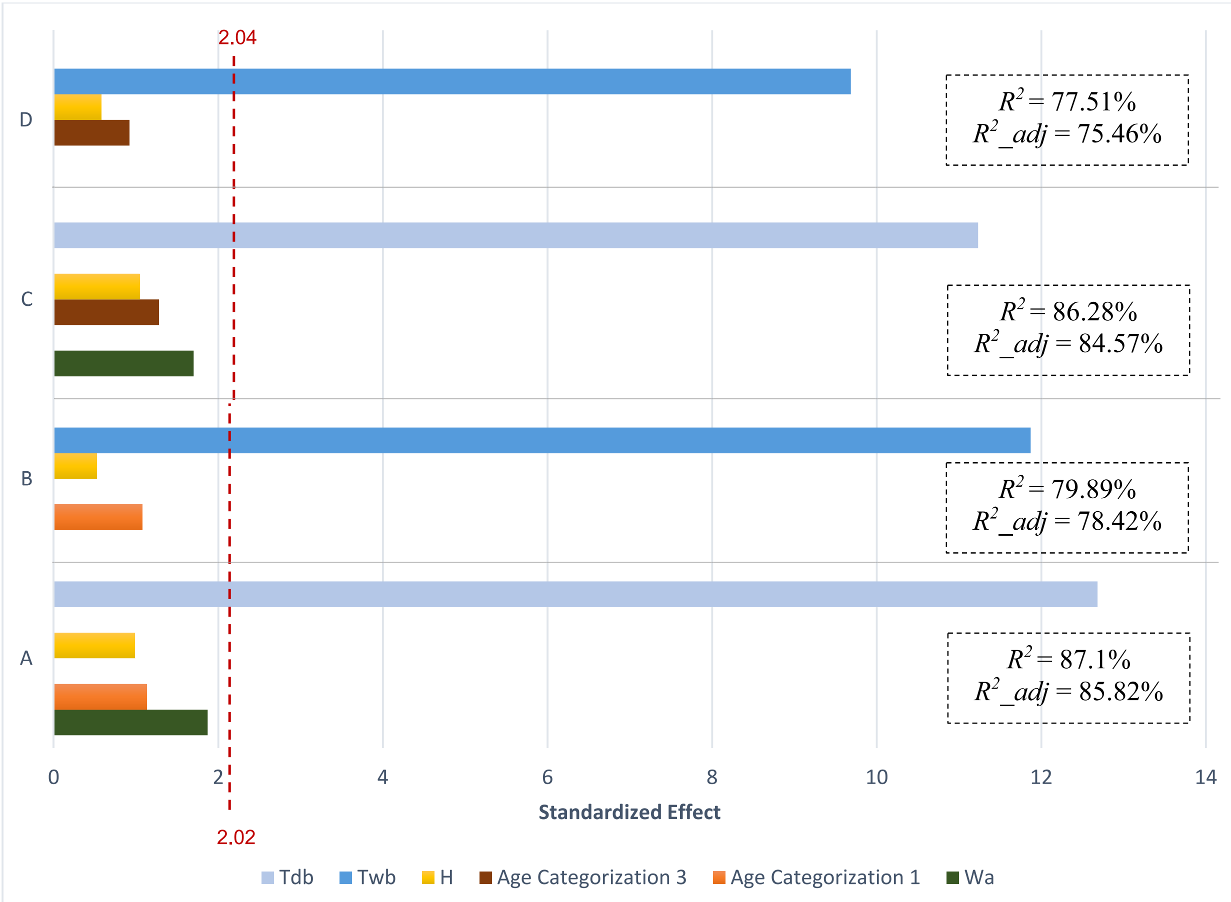

Fig. 6. Pareto Chart of standardized effects of T_{sk}. α = 0.05.

4.4. Predicting T_{sk}

Fig. 5 illustrates that as T_{db} increases, T_{sk} ceases to be a function of H and becomes solely dependent on T_{db}. Consequently, as the findings of this paper have shown that there is no statistically significant difference in T_{sk} between children and adults, and given the strong influence of environmental factors such as T_{db}, it is our recommendation to utilize the PHS (Predicted Heat Strain) regression model of T_{sk} for clothed subjects developed by Malchaire [17] to estimate T_{sk} for children. Based on data from 377 male subjects, the PHS regression predicts T_{sk} using 5 environmental factors and M (equation (25) with an R^2 of 59.29 %. It has been validated in a T_{db} range of 15 °C to 50 °C and an metabolic heat range of 100 W to 450 W, it can adequately predict T_{sk} for both children and adults in both mild and hotter environments, and while performing both moderate and strenuous activity.

$$T_{sk} = 12.17 + 0.02 \cdot T_{db} + 0.044 \cdot MRT + 0.194 \cdot pa - 0.253 \cdot v_a + 0.00297 \cdot M + 0.513 \cdot T_{cr} \quad (25)$$

5. Limitations

While this study offers advancements in assessing cooling loads from children by developing a child-specific heat balance model, it is important to acknowledge its limitations. As no comprehensive experimental study was found on children's sweating response in varied indoor environment conditions, we were compelled to use studies on children's thermoregulation in heat stress environments. Some of the environmental conditions included T_{db} greater than 30 °C which, though not unheard of in indoor settings [35], are unrepresentative of typical conditions encountered in mechanically cooled indoor environments. This can limit the generalizability of the regression predictions in more moderate environments. Additionally, the lack of a coherent methodology between the considered studies results in uncertainties. Key parameters such as VO_2, $\dot{m}_{sk}$, and exercise protocols are inconsistently reported across the literature, leading to reliance on approximations and secondary calculations. These data gaps can introduce uncertainties into the regression model's predictions. Certain parameters such as $\dot{m}_{res}$ are based on adult data due to the lack of child-specific measurements. These assumptions may not fully account for the physiological differences between children and adults. Future research should aim to make comprehensive measurements of child $\dot{m}_{sk}$, over several ranges of age, environmental conditions, and activity levels. It would also be beneficial to validate a child-specific heat balance model with experimental measurements.

6. Conclusions

In conclusion, the development of a child-specific heat balance model is both feasible and necessary, given the distinct physiological responses of children compared to adults. By modifying existing first-principles equations to account for children's unique characteristics, and using data from experimental studies in litterature, we created accurate regression models for predicting heat loss from sweating E_{rsw} as a function of H and T_{db} for both children as a whole (<18 y.o.), and for prepubertal children specifically. Not enough evidence was found to justify the need for a child-specific regression model for T_{sk}, and therefore adult regressions, like the PHS regression model, can be used in mild and thermally strenuous environmental conditions.

Similarly to past research on adults [17] our analysis demonstrated that environmental conditions, particularly T_{db}, have a significant impact on both T_{sk} and E_{rsw} for children, often overshadowing the influence of H. This demonstrates that models [21,37] calculating E_{rsw} and T_{sk} solely based on activity level, expressed in H, including in mild temperatures, fail to adequately account for the influence of T_{db}. The correlation between these variables underscores the limitations of existing adult-based models, such as Fanger's, which do not adequately consider the effects of higher temperatures [21,25,35]. The proposed model allows to calculate children's distinctive *SHR* for various activities and indoor environmental conditions, as needed to construct child-specific heat load tables. It offers a simpler option than transient, multi-segmented and multi-layered models, making it an excellent candidate for use in building performance simulation software. Future work should focus on gathering more comprehensive data on children's latent heat dissipation mechanisms and refining the equations to enhance their predictive capabilities, ultimately aiding in the design of indoor environments that are safer and more comfortable for children.

CRediT authorship contribution statement

Farah Youssef: Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Stéphane Hallé:** Writing – review & editing, Validation, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Katherine D'Avignon:** Writing – review & editing, Validation, Supervision, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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