Impact assessment of load bearing vests, combat armour and ventilated vest configurations on thermal strain

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Abstract. Dutch military personnel has access to a modular system of load bearing vests and combat armour that can be worn in combination with varying underlaying clothing. The equipment adds insulation and evaporative resistance, which may impact the environmental conditions that a military operation can be executed safely without risk of exertional heat stroke or other forms of heat illness. A ventilated vest worn under the load bearing vest may mitigate the heat burden. This study presents an assessment of the operational impact of load bearing vests and combat armour through measurements of thermal properties of clothing and equipment, combined with thermophysiological simulations. The insulation of the clothing and equipment configurations ranges between 0.68 clo and 1.03 clo; and the vapour permeability index ranges between 0.34 and 0.39. The impact of the equipment was larger on the warm climate clothing configuration than on the temperate clothing configuration. With inclusion of a ventilated vest worn under the load bearing vest the insulation ranges from 0.76 clo to 0.93 clo; and the vapour permeability index ranges between 0.41 and 0.46. The operational impact of the warm and temperate clothing configurations shows on average a 2˚C difference in air temperature before core temperature reaches 38˚C, and corresponds to an extended duration limit of exposure up to 4 hours. Finally, the ventilated vest on average compensated the added insulation range by −1˚C for warm climate clothing and −2˚C for temperate clothing configurations.

1. INTRODUCTION

Dutch military personnel has access to a modular system of load bearing vests and combat armour that can be worn in combination with varying underlaying clothing such as warm or temperate climate clothing. The equipment adds insulation and evaporative resistance, which may impact the environmental conditions that a military operation can be executed safely without risk of exertional heat stroke or other forms of heat illness.

This paper presents the outcome of a project for the NLD MoD concerning the assessment of the impact on thermal strain of load bearing vests and combat armour through measurements of thermal properties of clothing and equipment, combined with thermophysiological simulations [1]. Moreover the potential heat mitigating effect of an active ventilated vest, with channels to allow air flow, worn under the load bearing vest is incorporated [2].

The analysis provides a quantitative analysis to inform how protective clothing may influence heat strain and the potential effect size of wearing a ventilated vest. The information in this paper does by no means replace human experiments and should regarded as a sensitivity analysis to assess the impact on duration limit of exposure to warm environments; on top of that, the information can be used for time and cost-efficient design of experimental validation.

2. METHODS

Thermal manikin measurements of the thermal properties (clothing insulation and evaporative resistance) of load bearing vest and combat armour (equipment) configurations have been repeated for a warm climate clothing and a temperate climate clothing configuration. In total 18 configurations have been tested. Through this setup it is possible to study the effect of the interaction between the clothing and the equipment configuration on the thermal properties, for instance due to differences in compression of insulating air layers. Next, from a separate study the thermal properties of an active ventilated vest worn under the load bearing vest have been integrated into the results . Finally the operational impact has been estimated through simulation of heat balance with the ISO 7933 Predicted Heat Strain model [4]. The simulation encompassed a walking activity (6 km/h) without carried load for an unacclimatized person, and simulations were performed for a range of air temperature (20˚C to 40˚C) and relative humidity (10% to 100%). The output of the model is the time duration until core temperature reached 38˚C. The

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operational impact is defined as the difference in air temperature between configurations to reach core temperature equal to 38˚C.

2.1 Clothing and equipment configurations

The clothing configurations consisted of a warm climate battle dress uniform and a temperate climate battle dress uniform. On top of both uniforms several configurations of equipment were added with increasing protection level. A brief description of the clothing and equipment configurations and their respective configuration number are shown in Table 1.

Table 5: clothing and equipment configurations and corresponding configuration number. The grey rows are shown in the results section.

	Load bearing vest	Ballistics	Warm climate battle dress uniform	Temperate climate battle dress uniform
Uniform			1	10
Uniform and backpack			2	11
Uniform,	Front Chest rig at back Hip belt	Soft	3	12
Uniform and backpack	Front Chest rig at back Hip belt	Soft	4	13
Uniform	Front and back	Soft and hard	5	14
Uniform		Protection vest	6	15
Uniform	Front and back	Protection vest	7	16
Uniform	Front and back Hip belt	Protection vest	8	17
Uniform	Front and back Hip belt Add-ons	Soft and hard Protection vest	9	18

2.2 Thermal properties of clothing and equipment configurations

In the determination of the effect of clothing and equipment on heat dissipation from the body to the environment, two main parameters are of interest: the total insulation (I_T [m^{2}KW^{-1}]) and the total evaporative resistance ($R_{e,T}$ [m^{2}kPaW^{-1}]) [3]. The insulation of clothing can also be expressed in 'clo', 1 clo corresponds to 0.155 m^{2}KW^{-1}. The total insulation consists of the intrinsic insulation of clothing and equipment including enclosed air layers (I_{cl} [m^{2}KW^{-1}]) and the insulation provided by the surrounding air layer (I_a [m^{2}KW^{-1}]) (**Error! Reference source not found.**).

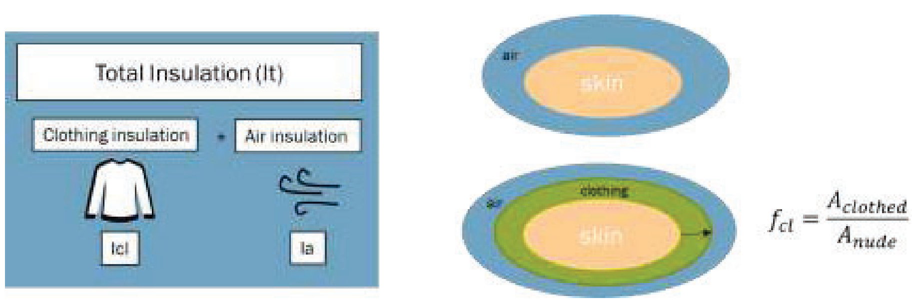

Figure 1: left, the total insulation consists of the intrinsic clothing insulation and insulation provided by the surrounding air layer. Right: clothing increases the surface area to exchange heat with the surrounding air layer. The increase in surface area is described by the clothing area factor f_{cl}.

The insulation values of clothing and the air layer do not simply add up to the total insulation (I_T [m^{2}KW^{-1}]). Clothing increases the surface area available for heat exchange with the environment; hence the insulation provided by air (expressed as m^{2}K/W) is inversely proportional to the increase of the surface area (**Error! Reference source not found.**, right). The reduction in insulation provided by a ir can be determined by correcting with the clothing area factor (f_{cl}: clothing area factor [-]); which is the ratio between the surface area of the outer clothing layer ($A_{clothed}$) and body skin (A_{nude}). Following the above the total insulation of a clothing configuration can be described as:

$$I_T = I_{cl} + \frac{I_a}{f_{cl}} \left[\frac{m^2K}{W}\right] \tag{1}$$

The total evaporative resistance ($R_{e,T}$ [m^2kPaW^{-1}]) is described analogous to the total insulation of clothing and air and consists of a clothing-intrinsic evaporative resistance ($R_{e,cl}$ [m^2kPaW^{-1}]) and evaporative resistance provided by the air layer ($R_{e,a}$ [m^2kPaW^{-1}]): the latter again has to be corrected with the f_{cl}:

$$R_{e,T} = R_{e,cl} + \frac{R_{e,a}}{f_{cl}} \left[\frac{m^2kPa}{W}\right] \tag{2}$$

From the total insulation and total evaporation resistance the permeability index is be calculated as follows:

$$im = \frac{I_T}{16.5\ R_{e,T}} \tag{3}$$

The value 16.5 [K kPa^{-1}] corresponds to the Lewis relation for evaporation at sea level and is a function of air pressure.

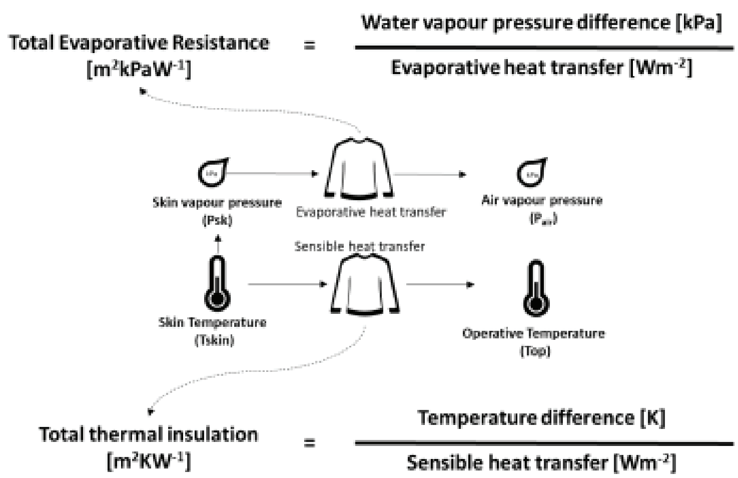

Figure 2: Total thermal insulation (I_T) is equal to the temperature difference between skin tissue and the surrounding air layer per unit of sensible heat transferring through the surface area. Sensible heat transfer is an all-purpose word for conductive, convective and radiative heat transfer. The total evaporative resistance ($R_{e,T}$) is equal to the vapour pressure difference between skin and the surrounding air layer per unit of heat equivalent to the evaporated water that is transferred over the surface.

The thermal properties are measured using a thermal manikin at Centexbel (Belgium). The thermal manikin consists of several segments for which the surface temperature can be regulated with a heat source (Figure 3). The thermal resistance per zone (i) consists of the resistance generated by the clothing (I_{cl}) [m^2KW^{-1}] and by the air layer (I_a) [m^2KW^{-1}]. The total resistance value for the whole body is determined according to the parallel method where the zones are weighted by the relative area:

$$I_T = \frac{A_{tot}}{\sum \frac{A_i}{I_i}}$$

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with A_{tot} [m^2] the total area, A_i [m^2] the local area, and I_i [m^{2}KW^{-1}] the local insulation value. For the evaporative resistance an analogous method is used.

Zones	name
1	face
2	head
3	right upper arm
4	left upper arm
5	right forearm
6	left forearm
7	right hand
8	left hand
9	chest
10	shoulder
11	stomach
12	back
13	right hip front
14	right hip back
15	left hip front
16	left hip back
17	right thigh front
18	right thigh back
19	left thigh front
20	left thigh back
21	right calf front
22	right calf back
23	left calf front
24	left calf back
25	right foot
26	left foot

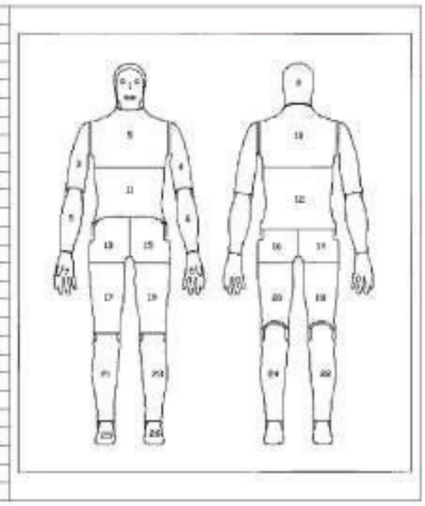

Figure 3: thermal manikin and division into segments.

The measured thermal properties are listed in Table 2. Moreover Table 2 also lists the thermal insulation values with ventilated vest over the torso. These values are estimated by substituting measured local values of the chest, shoulders, stomach and back (segments 9 through 12), with values measured with a ventilated vest system [2].

Table 6: clothing and equipment configuration thermal properties

Configuration	I_{cl} [m^{2}KW^{-1}]	im_{st} [-]	I_{cl} [m^{2}KW^{-1}]	im_{st} [-]
Warm Climate Clothing	Without ventilated vest	Without ventilated vest	With ventilated vest on torso	With ventilated vest on torso
1	0.105	0.39	0.118	0.46
3	0.122	0.38	0.122	0.44
9	0.140	0.37	0.131	0.43
Temperate Climate Clothing	Without ventilated vest	Without ventilated vest	With ventilated vest on torso	With ventilated vest on torso
10	0.137	0.36	0.136	0.43
12	0.147	0.36	0.141	0.43
18	0.159	0.35	0.145	0.41

2.3 Predicted heat strain according to ISO 7933

To gain insight into the operational impact of the clothing configurations, a simulation was performed using the model described in ISO 7933 (Predicted Heat Strain) [4]. The simulation performs a calculation of the physical heat balance to calculate the course of a person's core temperature and sweat loss given the weather (environment), personal characteristics, activity and clothing properties. The time (in minutes) to reach a core temperature above 38˚C has been used, which corresponds to the standard duration limit value ($Dlim_{T,RH}$) as described in ISO 7933. Moreover, the duration limit of exposure difference between specific configurations ($\Delta Dlim_{T,RH,i,j}$, configuration i vs. configuration j) is

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determined by subtracting the corresponding values for each air temperature (T) and relative humidity (RH):

$$\Delta Dlim_{T,RH,i,j} = Dlim_{T,RH,j} - Dlim_{T,RH,i}$$

In order to provide an overview of the influence of temperature and air humidity, the simulations have been performed for a range of air temperature and air humidity; see Table 3 for details.

Table 7: input values for simulation of the Predicted Heat Strain model.

Type	Variable	Value or range	Unit
Environment	Air temperature	20 tot 40	˚C
	Relative humidity	0 tot 100	%
	Air velocity	0.6	m/s
	Mean radiant temperature	5 ˚C above air temperature	˚C
Person	Mass	80	kg
	Height	1.8	m
	Position	Standing	-
	Acclimatisation state	0 (not acclimatized to heat)	-
Activity	Metabolic heat production	415	W
	External work	0	W
	Walking speed	6	km h^{-1}
Clothing	Intrinsic clothing insulation	See Table 3 (column Icl)	m^2KW^{-1}
	Water permeability index	See Table 3 (column im_{st})	-
	Fraction covered by reflective clothing	0.54	-
	Emissivity of reflective clothing	0.97	-

3. RESULTS

The predicted time taken to reach a core temperature of 38˚C during marching on an overcast day is shown in Figure 4 for a selection of the clothing and equipment configurations. The left column shows the results for warm climate clothing and the right column shows the results for temperate climate clothing. The dotted guides show how the results differ per configuration. Comparison of the top and bottom rows shows that the most insulating vs. least insulating configuration corresponds with an air temperature shift of about +2 ˚C for warm climate clothing and +1 ˚C for temperate climate clothing.

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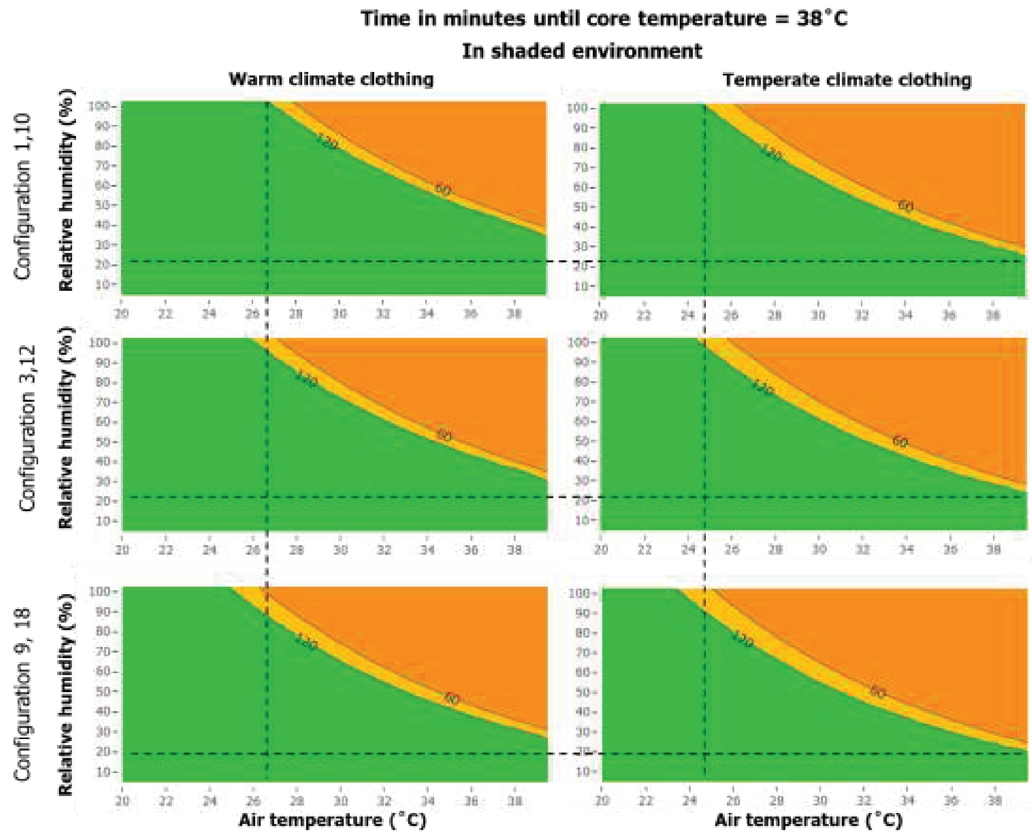

Figure 4: Duration in minutes until the core temperature reaches 38˚C during marches (6km per hour). The green zone indicates that it takes longer than 2 hours to reach 38˚C. The yellow zone indicates that it takes between 1 hour and 2 hours to reach 38 ˚C and the orange zone indicates that it takes less than 1 hour to reach 38 ˚C.

The temperature shift can lead to significant changes in duration limit of exposure, which is illustrated in Figure 5. For many combinations of air temperature and humidity the difference in duration limit of exposure to reach a core temperature of 38˚C is less than an hour (shown as white area), however, the green zone depicts combinations of air temperature and humidity for which the time difference can increase to up to 4 hours. This means that the potential negative effect of added insulation on thermal strain is dynamic over the weather context. Interestingly, and actually adding to the complexity, the positioning of the green zone is not fixed and varies over clothing configurations. The analysis makes clear for human experiment design, the expected maximum effect size in thermal performance requires specific environmental conditions per clothing configuration. On top of that, not shown in Figure 5, but the positioning of the green zone is also dependent on the activity level (higher activity level means the green zone shifts to left), the prevailing wind speed (higher wind means the green zone shifts to right), and the presence of a radiant heat source (higher solar radiation means the green zone shifts to left).

Analogous to the comparison of clothing configurations operational effect on body temperature, also the potential effect of a ventilated vest on body temperature has been studied. The use of a ventilated vest can compensate 1˚C for the warm climate clothing configurations to 2˚C for the temperate climate conditions. The effect on extension of duration limit of exposure for selected clothing configurations is shown in Figure 6. Again the white zones correspond to less than 1 hour difference for the configurations to reach core body temperature of 38 ˚C; whereas in the green zone the difference becomes larger than 1 hour and can even increase to 4 hours. The analysis indicates that ventilated vests can be both crucial for the maintenance of operational capabilities in specific thermal environments, yet at the same time there are also many combinations of humidity and air temperature for which little difference in thermal strain can be expected.

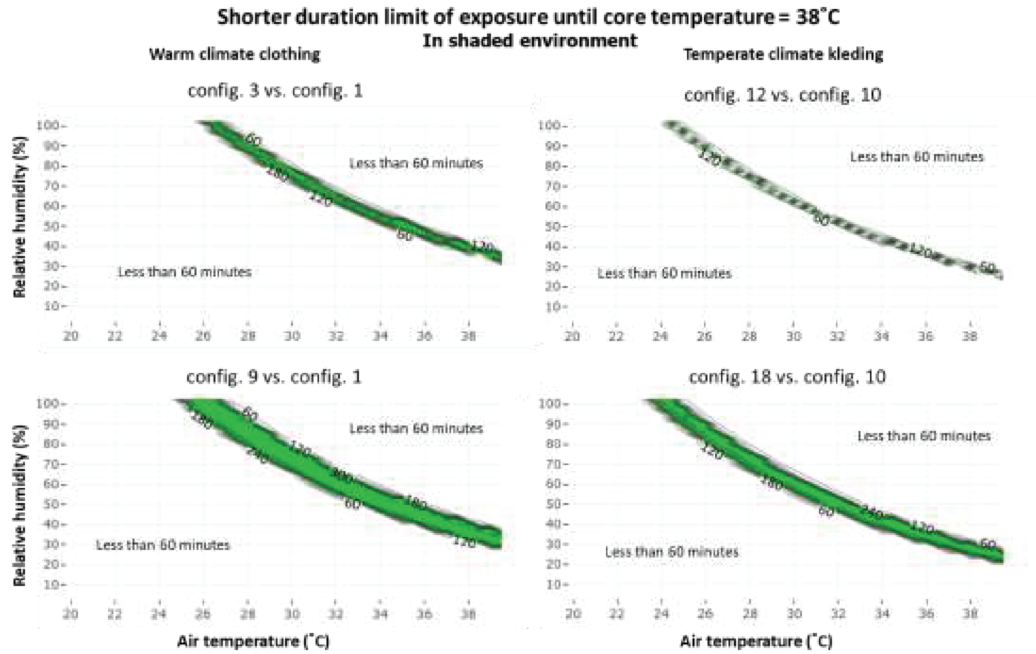

Figure 5: Difference in duration to reach 38˚C (in minutes) comparison for specific clothing and equipment configurations. Example: in the white area, the difference in time to reach 38°C is less than 1 hour for both configurations, within the green zone there is an expected difference in the duration before core temperature reaches 38 ˚C for both configurations.. The green area increases rapidly and can save up to 4 hours for specific combinations of temperature and humidity**.** The larger the difference in clothing properties, the larger the green zone.

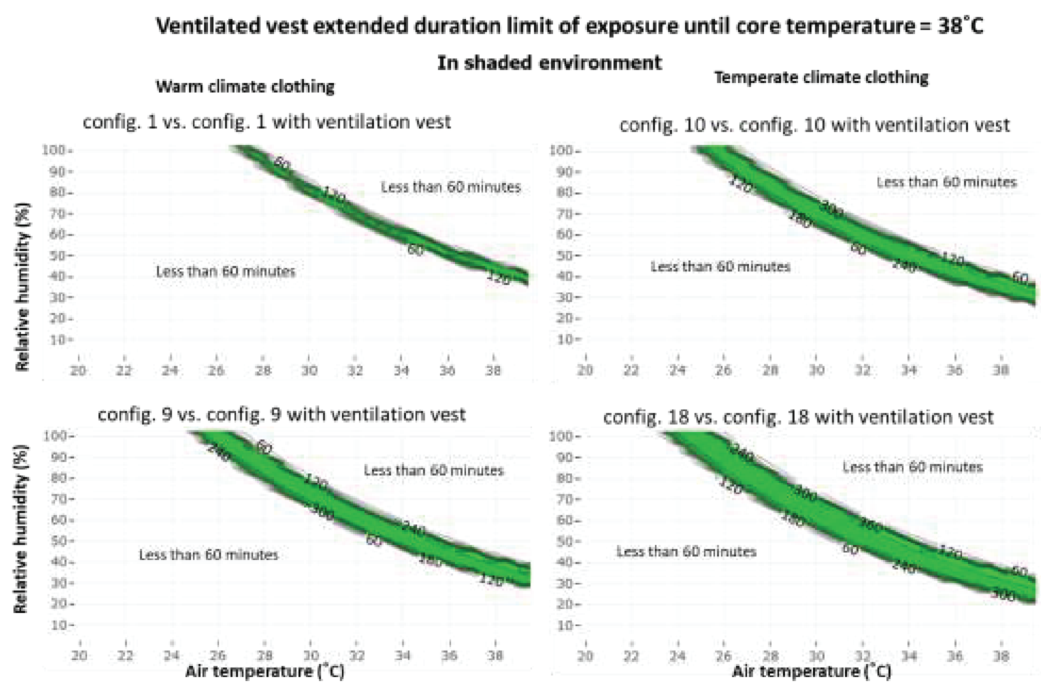

Figure 6: Extended duration to reach 38˚C (in minutes) when using a ventilated vest comparison for specific clothing and equipment configurations. In the white area, the difference is less than 1 hour. The green area increases rapidly and can save up to 4 hours for specific combinations of temperature and humidity**.**

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4. DISCUSSION

The present analysis provides an overview of the impact of load bearing vests and combat armour on thermal strain. Moreover, the potential mitigating effect of a ventilated vest is quantified. In general terms highest insulating configuration has an impact that is comparable to that the air temperature is 2˚C warmer. This result is comparable to NATO recommendations to add 2.8˚C to wet bulb globe temperature thresholds when wearing combat armour [5]. Moreover, these 2˚C can be operationally relevant as the duration limit of exposure can differ up to 4 hours for specific combinations of temperature and humidity (see Figure 5). A ventilated vest worn under the load bearing vest can potentially mitigate the thermal burden provided by the load bearing vest and extend the duration limit of exposure. The analyses show that the effect size of the added insulation or potential benefit of a ventilated vest on duration limit of exposure is highly variable over environmental conditions (see green zone in Figure 6), and can thereby inform decision support in an operational setting; or support the design of human experiments for the validation of the simulation results.

The comparative analyses between clothing configurations shown in Figure 5 indicate that it is perfectly possible to find little operational effect on the thermal burden for specific environmental conditions (white areas). However, in the green area's the difference in duration to reach a body core temperature of 38 ˚C can lead up to 4 hours. Analogous, Figure 6 indicates that the effect of a ventilated vest to extend the operational duration limit of exposure is also highly dependent on the exact environmental conditions. The width of the green zone, (see for example the panels for configuration 1 vs. configuration 18 in Figure 6), is apparently related to the corresponding difference in clothing insulation and evaporative resistance. The location of the green zone is further dependent on the prevailing wind speed, solar radiation, activity level and the acclimatisation state of the person.

The analysis of the heat load according to ISO 7933 is a model study and is in no way a substitute for experimental values. The results of the simulation can be interpreted as a sensitivity analysis to estimate the effect of the different insulation values on heat strain. The simulation in this report does not take into account biological variation and its impact on heat production and/or the ability to transfer heat to the environment. Furthermore, the simulation assumes one continuous activity level on a flat paved road. The increase in heat production due to the extra weight carried by the clothing and equipment configurations has not been included. This simplification may lead to an underestimation of the effect of the heat load. Next, part of the simulation performed with ISO 7933 Predicted Heat Strain model extends beyond the range of validity of humidity that the model claims to be valid (vapour pressure range between 0 and 4.5 m^2kPaW^{-1}); this means that for combinations of high humidity and air temperature (top right parts of Figure 4, Figure 5 and Figure 6) the model simulation validity is not defined. Since none of the operational differences are found in the top right corner of the corresponding Figures, the effect on the analysis interpretation is considered minimal.

5. CONCLUSION

The added insulation and evaporative resistance of protective equipment on military clothing configurations has been measured; and the operational impact has been simulated with the Predicted Heat Strain model (ISO 7933). Moreover the beneficial effect of a ventilated vest on thermal properties has been calculated. The most protective configuration shows an operational impact on average of 2˚C air temperature during a marching activity, which may correspond to up to 4 hours decreased duration limit of exposure. A ventilated vest worn under the load bearing vest has the potential to compensate the added insulation by 1˚C. The analyses show that the effect size of the added insulation or potential benefit of a ventilated vest on duration limit of exposure is highly variable over environmental conditions.

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