

The Metabolic Rate of Male Adults in Different Garments Under Different Upper Limb Workloads

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Abstract While we are working or living in severe environment, the internal pressure changes of functional garments, the resistance from clothing and the thermal insulation for individual will lead obviously changes of our workload, heart rate and metabolic rate. Working in extreme circumstances and dressing pressure garments make workload increased significantly which limit people's ability to accomplish the tasks and reducing the efficiency of activity. This paper mainly report the study on relationship between different upper limb workloads and metabolic rate when subjects were dressing, undressed or with pressures. Specially, we focus on the relationship between heart rate and metabolic rate in clothes. The main conclusions of this paper is: Wearing different garments the correspondence between heart rate and metabolic rate are far from the same. And Liquid Cooling Garment (LCG) is the most effective garment for human metabolism among the clothes in this research. The pressures inside clothes increased workload, as well as the metabolic rate.

Keywords Metabolic rate · Heart rate · Workloads · Garment · Ergonomics

1 Introduction

Influence of clothing on human metabolism is through the separation of human body from external thermal exchange and the resistance of the clothing which increase workload. Besides, the change of pressures inside airtight garment will lead metabolic rate (MR) to increase. From 1940s, people began to pay attention to the effect of clothing thickness on heat transfer between human body and the environment [1]. In 1960–70s, Woodcock et al. have proposed thermal dynamic

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models about clothing human body heat transfer to the environment [2–7]. However, the effect of different clothing on human metabolism is rare. Typically, the metabolism occurred corresponding change which caused by the clothing heat barrier and pressures change in different attire can often be ignored, and been ignored in the past. But with the continuous expansion of human activity scope, people need to wear special costumes in extreme environment, those effects on human metabolism should not be neglected. For example, in a vacuum and cold space people need to wear the garment with thermal protection and pressure regulation functions, which will prevent our body from hurting by surroundings. Meanwhile, it blocks physical heat dissipation and increases the resistance, so does the metabolic rate.

Extreme environments often requires the clothing have such functions as adiabatic, pressure and thermal regulation, with the change features of peripheral environment and the metabolic heat production, increase the workload significantly. It greatly limits the ability of people to complete the tasks, reducing the activity efficiency. Therefore, research on the relationship between workloads and metabolism in different suits help people understand the relevant issues and provide the reference for human activity in bad environment. This paper study on the effect of different clothes and different clothing pressures on workload, heart rate and metabolic rate by experiment. And the method of metabolism relevant data acquisition mainly come from ISO 8996:2004 Ergonomics of the thermal environment-Determination of metabolic rate. The researchers adjusted the measurement and calculation method of the standard and improved it better meet the Chinese physical condition.

2 Method

Researchers designed the primary coverage of this study which was the measurement of the heart rate and respiratory related parameters while subjects were trying to accomplish different loads of upper limb exercises in different garments or pressures. Calculating the body's metabolic rate and then observing the relationship between metabolic rate and heart rate under the different clothes.

The researchers obtained metabolic rate by measured the parameters related to human breathing, like carbon dioxide production rate and oxygen consumption rate. The metabolic rate is calculated by using these parameters. According to ISO 8996:2004 [8], the computational formula of respiratory quotient (RQ) is as follows:

$$RQ = \frac{\dot{V}_{CO_2}}{\dot{V}_{O_2}} \quad (1)$$

The energetic equivalent EE ($W \cdot h/L$) and the metabolic rate M (W/m^2) is calculated as:

$$EE = 5.88 \times (0.23 RQ + 0.77) \quad (2)$$

$$M = EE \times \dot{V}_{O_2} \times \frac{1}{A_{Du}} \quad (3)$$

Among these formulas, \dot{V}_{O_2} and \dot{V}_{CO_2} respectively represent the oxygen consumption rate and carbon dioxide production rate in liters per hour which these two values can be acquired by measuring, A_{Du} stands for the body surface area which is given by the Du Bios formula which is:

$$A_{Du} = 0.202 \times W_b^{0.425} \times H_b^{0.725} \quad (4)$$

H_b is the body height in meters, W_b is the body weight in kilograms.

Through the consolidation and adjustment of the calculation methods in standard, we obtained the basic formula of metabolic rate M which can be computed directly by respiratory parameters as:

$$M = \left[5.88 \times \left(0.23 \times \frac{\dot{V}_{CO_2}}{\dot{V}_{O_2}} + 0.77 \right) \right] \times \dot{V}_{O_2} \times \frac{1}{A_{stevenson}} \quad (5)$$

In this equation, $A_{stevenson}$ is the body surface area which is figured by the Stevenson formula as:

$$A_{stevenson} = 0.61 H + 0.0128 W - 0.1529 \quad (6)$$

We used $A_{stevenson}$ instead of A_{Du} to calculate body surface area is because it is more suitable with the physical condition of Chinese. The values of metabolic rate in this research are all figured by the formula (5) and (6).

The researchers chose 10 healthy male adults whose body height was between the 161–179 cm and weight was in 52–77 kg, then, conducted participants performed upper limb exercise according to a certain rhythm in different clothes or pressures. At the same time, we recorded the heart rate, oxygen consumption, respiratory quotient and other relevant physical parameters.

The conditions of garment and pressure included as: naked (only wore shorts), wore undergarment, wore Liquid Cooling Garment (LCG) with undergarment at normal temperatures and pressures (Fig. 1), two pressure garments with 130 and 140 kPa absolute pressures, which contained airtight pressure suit with LCG and underwear.

We designed the work situation in nude, underwear and LCG tests which included static standing, shoulder rotation, elbow rotation and upper limb movement which the output power at 20, 30, 40 and 60 W with only some subjects completed 70 W power of upper limb exercise test. Test work in pressure garments



Fig. 1 Status of subjects in undergarment and LCG

is static standing, elbow rotation and two kinds of workload of upper limb exercise. Single mode measurement time is 2–3 min and rest 3–5 min, the rest time based on whether subjects recovered to their basal metabolic rate.

Finally, the test personnel checked the instruments for measurement of respiratory parameters and heart rate, the measurement accuracy reached at 0.01 L/h.

3 Result

The tests obtained subjects' heart rate and metabolic rate during upper limb movement in five kinds of clothes with conditions. The heart rate (HR) and metabolic rate (MR) of Subject No.1 following the change of time in all kinds of clothes and workloads, as it shown in Figs. 2, 3, 4, 5 and 6.

According to the periodic filtering of sample points of heart rate and metabolic rate, subjects in LCG status are the most efficient, which in the same level of heart rate (90–120 b/min) can provide 37.56–104.59 % more power than any other state. The results of other 9 subjects are similar to subjects No.1. Furthermore, researchers figured out the average heart rate and average metabolic rate in a period of time, the fitting curve of the mean metabolic rate and mean heart rate in the condition of different clothes, as shown in Fig. 7.

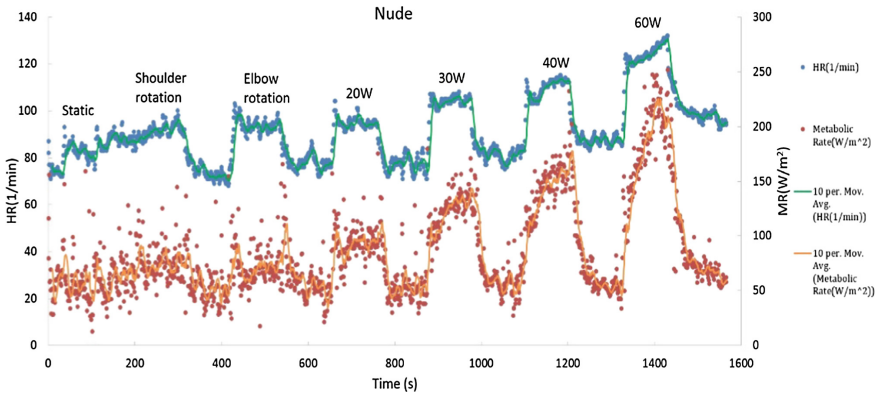


Fig. 2 HR-MR variation over time at nude status

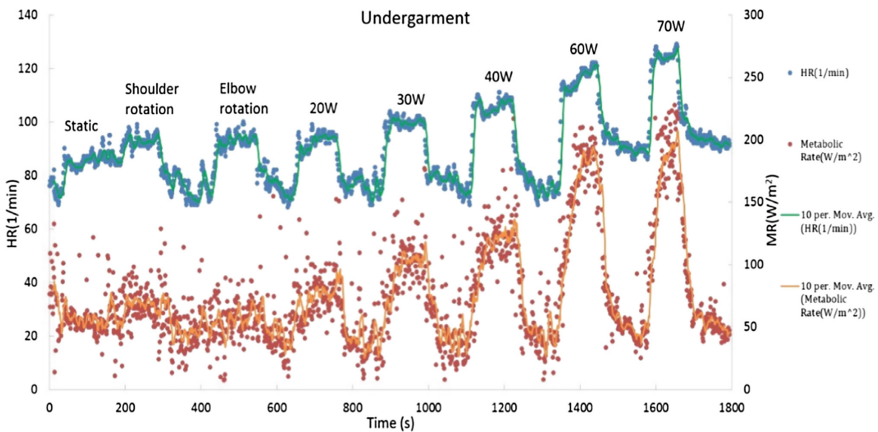


Fig. 3 HR-MR variation over time at undergarment status

Let X denote the average heart rate, Y represents the average metabolic rate. Curve fitting the results obtained average heart rate—metabolic rate relationship of subjects No.1 in different garments:

- Nude: $Y = 2.61X - 152.57, R^2 = 0.8171$
- Undergarment: $Y = 2.53X - 153.52, R^2 = 0.8011$
- LCG: $Y = 5.05X - 352.13, R^2 = 0.8103$
- 130 kPa Suit: $Y = 3.62X - 152.88, R^2 = 0.6414$
- 140 kPa Suit: $Y = 2.80X - 146.48, R^2 = 0.7053$

Meanwhile, the different subjects in the same suit have different relationship between metabolic rate and heart rate. Figure 8 for instance, it contains 10 subjects’

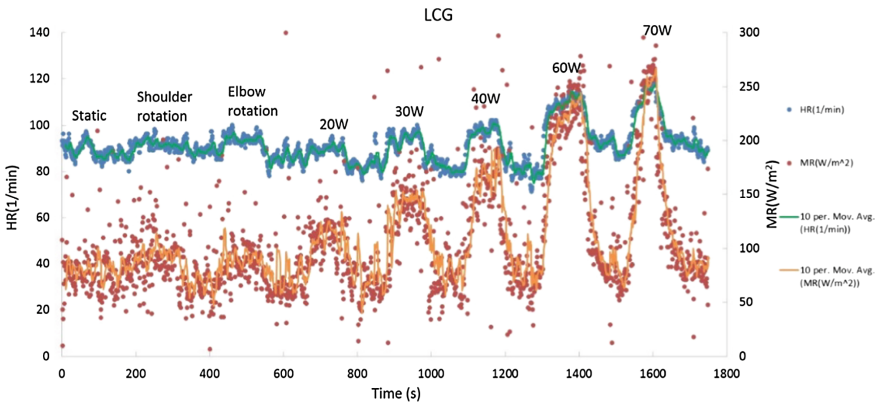


Fig. 4 HR-MR variation over time at LCG status

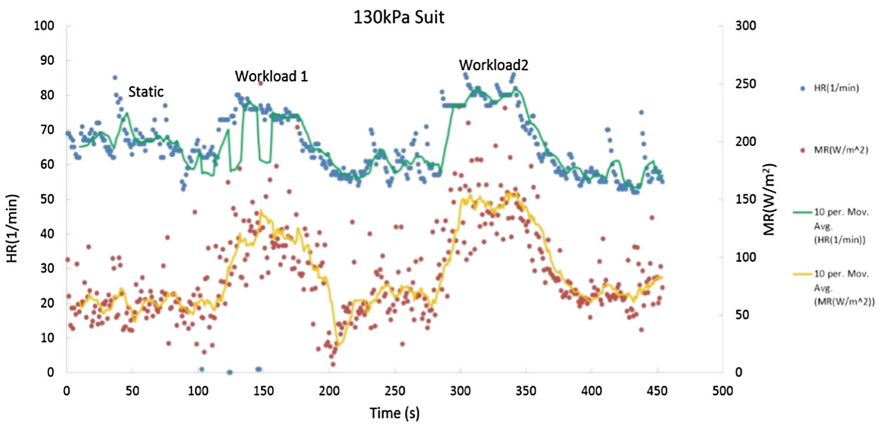


Fig. 5 HR-MR variation over time at 130 kPa pressure suit status

average HR-MR fitting curve in 130 kPa suit, which results is summarized in Table 1.

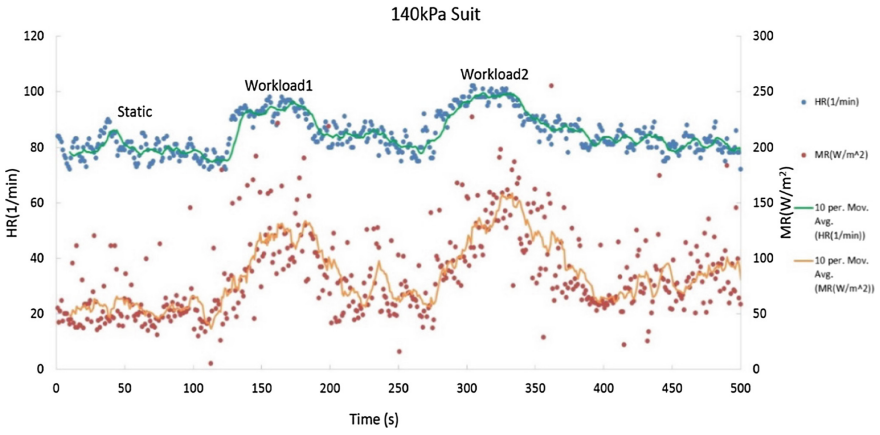


Fig. 6 HR-MR variation over time at 140 kPa pressure suit status

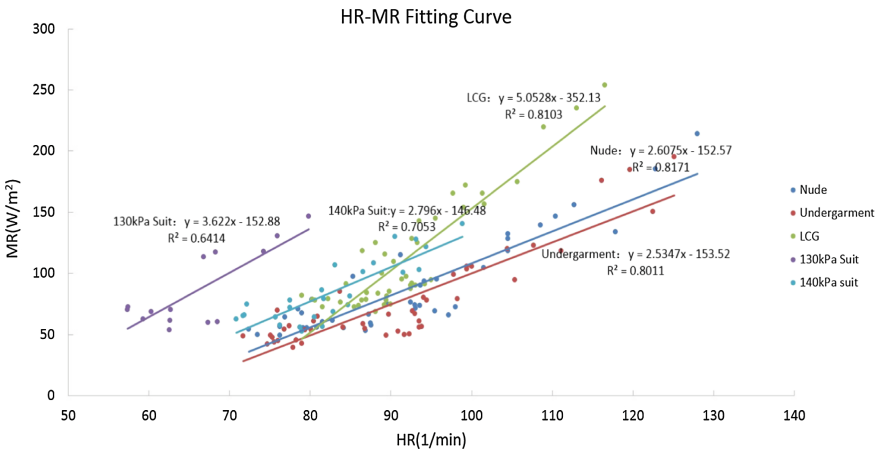


Fig. 7 The fitting curve of average HR-MR in the different clothes

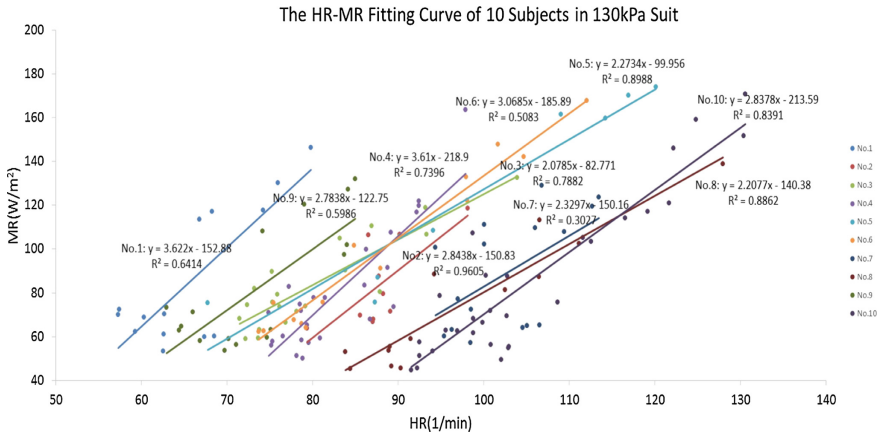


Fig. 8 The fitting curve of 10 subjects' average HR-MR in 130 kPa suit

Table 1 Parameters of HR-MR Fitting Curve from 10 subjects in 130 kPa Suits. Let $Y = aX + b$

Subject	High/m	Weight/kg	a	b	R ²
1	1.75	76.66	3.62	-152.88	0.6414
2	1.72	56.34	2.84	-150.83	0.9605
3	1.66	64.59	2.08	-82.77	0.7882
4	1.72	67.16	3.61	-218.90	0.7396
5	1.61	52.27	2.27	-99.96	0.8988
6	1.66	60.74	3.07	-185.89	0.5083
7	1.70	65.09	2.33	-150.16	0.3027
8	1.79	63.26	2.21	-140.38	0.8862
9	1.70	60.12	2.78	-122.75	0.5986
10	1.74	64.70	2.84	-213.59	0.8391

4 Conclusion

Researchers draw the following conclusions according to the results:

According to Figs. 2 and 7, the same subject in different garments have different correspondent relations between heart rate and metabolic rate. The stronger resistance of clothes, the smaller slope of HR-MR fitting line (LCG > Nude > Undergarment, 130 kPa suit > 140 kPa suit). The clothing resistance here is not only refer to mechanical obstruction, but also mean the impediment of thermal regulation. In fact, people have a stronger capability of cooling when they are in LCG than only in underwear or nude status. Meanwhile, it has better flexibility than pressure suits. As the result shows to us, when people in LCG they could

provide 37.56–104.59 % more power in the same situation (heart rate at 90–120 b/min) than other garments. Therefore, LCG is the most efficient metabolic suit.

Figures 5, 6 and 7 shows that 130 kPa suit has higher metabolic efficiency than 140 kPa suit. It suggests that with the growing pressures inside the suit, it consumes more power to accomplish the same task. So pressures increase the workload and rise up the metabolic rate to some extent.

The HR-MR relationships of the different subjects in the same clothing are not the same and with no apparent connection to their own naked status. It may be related to the relationships of HR-MR vary from person to person.

Although nude or wearing undergarment status have almost no clothing resistance, they are not the most efficiency state of metabolism. It supposed to that through the body skin directly to exchange the energy with the out world may not the most efficiency way. The equipment like liquid cooling garment can make physical work more efficient.

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