The effect of back-loaded distribution on metabolic energy and subjective fatigue : An ergonomic evaluation for the development of a new personal protective respirator

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Introduction

The global pandemic of COVID-19 has made us aware of the importance of personal safety and protection than ever before (Fauci et al., 2020; Khan & Prab, 2020). And thus, there are growing interests among general public in wearing personal protective equipment (PPE), along with powered air purifying respirators (PAPRs), which has been mainly used by medical personnel and first responders (Lu et al., 2020; Patel, 2020). While it offers additional protection, wearing PPE likely causes increased metabolic energy cost due to extensive load bearing and inertia on the human body (Keren et al. 1981; Martin, 1985). Moreover, the required metabolic energy increases proportionally to the wearer's weight, and further it is affected by the location and distribution of the load that the wearer carries (Daffin et al., 2020; Kim & Lee, 2013; Pedersen et al., 2007; Rugelj & Sevšek, 2011). In this study, we are ultimately interested in developing a new personal protective respirator, as an alternative to the current medical PAPR that consists of face shield, battery pack, filter, hose with a total weight of 5.89kg (l2.98lbs.). To this end, the particular purpose of this study was to quantify the amount of metabolizable energy changes by the different load conditions of a PAPR, specifically by the load's position and distribution on the wearer's back in running mode. We also compared subjective fatigue with the metabolic energy cost, in order to gauge a psychological stress as well as a physical burden, imposed on the wearer, while wearing a PAPR.

Methods

The participants of the experiment were 10 healthy adults who had no neuropathic and cardiovascular diseases, and was involved in running exercise at least 30 min/week in the last 3 months. Prior to the study participation, the participants were given a brief overview of the study procedures and allowed to ask any questions about the study or data collection procedures. When they agreed to participate, they signed the consent, and participated in the experiment.

For the actual experiment, they were asked run on a treadmill, carrying a total load of 4.4 kg on the back. The weight used in the experiment was determined by the combined weight of a PAPR (1.4 kg) and an emergency backpack (3 kg), simulating a probable emergency escape/rescue scenario case. After a stretching and running warm-up for 5 minutes, the participants partook in a 7-min flat-land running task at the speed, set as the rate of transition from walking to running calculated along the length of the participant's legs, in reference to Hreljac (1995). The loads of the PAPR and emergency backpack, adopted in this study, were estimated based on the average of technical specifications of commercially-available products. For the running task, we used an acrylic plate weighing 1.4 kg attached to the waist, specifically at the posterior superior Iliac Spine (PSIS), and two water sacs (1.5 kg x 2) were placed on the participant's back according to the following two positioning conditions: stacked at the center (condition A) and dispersed on the back (condition B) (see Figure 1). The order of the experimental conditions was randomized. The participant's metabolic energy cost was measured by a portable radio respiratory gas analyzer

(COSMED K5, COSMED srl, Rome, Italy) and a heart rate tester (HRM-Dual, Garmin, Kansas, USA). Upon the completion of the running task, the participants were asked to evaluate on their subjective fatigue perception using a survey questionnaire containing 34 questions about whole and local body pain and discomfort across the body. The collected metabolic variables, including oxygen consumption per minute, heart rate, respiration rate, energy consumption per minute and the number of steps per minute were analyzed and compared by the experimental conditions via. paired-samples t-tests at $p < .05$.

Results

The average respiratory gas strain was measured for the last two minutes of the 7-min running. At this point, the steady state was defined as a state in which the mean value for the last minute of oxygen consumption per minute differed by no higher than 100 ml/min from the average value for the previous minute, confirmed that it had been reached. The t-test results showed no significant difference between condition A and B in all four variables (oxygen consumption per minute, heart rate, respiration rate and energy consumption per minute). Further, vertical ground reaction and pressure center data of each foot step were collected using a treadmill with built-in pressure sensors. The data was collected for five minutes, since the first two minutes of the 7-min running were excluded from analysis considering the adaptation time. As for the total number of steps per minute, there was no significant difference among the unweighted condition (no load), condition A and condition B. The results of the quantitative data did not signify the effect of the different load conditions on the participants' metabolic energy at the 95% confidence level. On the other hand, the results of the participants' subjective fatigue perception added an interesting perspective to the study. That is, the values of condition B showed significantly higher scores in the upper back (p=0.085), front thigh (p=0.028), back calf (p=0.061) and ankle (p=0.007) than those of condition A, which indicated that the participants experienced greater fatigue when running in the dispersedly distributed back-load condition than when the loads were concentrated at the lower back.

Body part	*Condition*		*p*
	A	**B**	
whole body	0.90(1.101)	1.30(1.567)	2.974
upper back	1.80(1.814)	2.00(2.055)	0.375
abdomen	1.60(1.955)	1.90(1.792)	0.388
lower back	2.10(2.132)	2.90(2.079)	0.085*
thigh back	1.00(1.414)	1.60(1.776)	1.112
thigh front	1.80(1.814)	1.90(1.792)	0.028*
calf back	2.00(1.764)	2.10(1.792)	0.061*
calf front	2.00(1.944)	2.00(2.000)	0.300
ankle	2.20(2.486)	2.40(2.271)	0.007*

p= *<0.1, ** <0.05, * <0.01, N=10*

Conclusion and Implications

This study revealed that although there were no significant differences in the quantitative data, subjective fatigue perception generated meaningful results with regards to the effect of different load distributions when carrying necessary personal protective equipment potentially used during future disasters. It also suggested the importance of the mixed-methods approach concerning both objective and subjective perspectives, particularly when data deal with complicated human experiences. The outcome of this study is expected to provide a practical foundation in developing new PPE with improved comfort and usability.

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