PREDICTION OF METABOLIC ENERGY COST FROM UPPER BODY ACCELERATIONS

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ABSTRACT

Upper body accelerations were measured from human subjects as they walked on a treadmill at different speeds and inclines, while carrying different loads in a backpack. Metabolic energy cost was also measured using indirect calorimetry. The objective of the study was to determine if metabolic energy cost, under the above conditions, can be reliably estimated from upper body accelerations. Several parameters were extracted from the acceleration signals, and used in a multiple regression analysis. A statistical model, derived using the acceleration parameters as independent variables and energy cost as the dependent variable, explained 60% of the variance in the measured energy cost. If load was included with the acceleration parameters in the model, 72.3% of the variance was explained. These results indicate that a reasonable estimate of physiological workload can be obtained from upper body accelerations, if the load carried is known.

I. INTRODUCTION

It is known that many factors can affect the workload or metabolic energy cost associated with an activity. In particular, the physiological demands of locomotion – walking and running – have been studied extensively and it has been found that the metabolic energy cost of locomotion is affected by speed, the gradient of the terrain, body size, load carried and gravity [4, 7]. Researchers have attempted to develop predictive equations for the metabolic energy cost of locomotion. Pandolf et al. [6] derived the following equation for the metabolic cost of walking while carrying a loaded backpack:

$$M_W = 1.5W + 2.0(W+L)(L/W)^2 + \eta(W+L)[1.5V^2 + 0.35VG]$$

where M_W is the metabolic rate (kcal/h), η is the terrain factor, W is the body weight (kg), L is the external load (kg), V is speed (km/h), and G is grade (%). The equation predicts metabolic cost with an $R^2 = 0.92$ under specific conditions. However, it significantly overestimates the metabolic cost of walking or running at speeds higher than 2.2 m/s. Thus, Epstein et al., [2] developed a model for energy cost of load carriage while running:

$$M_r = M_W - 0.5(1-0.01L)(M_W - 15L - 850)$$

where M_r is the metabolic cost of running and the other variables are the same as above.

Metabolic energy expenditure is measured in a number of ways; the most common is indirect calorimetry, in which the rate of oxygen consumption ($\dot{V}O_2$) and carbon dioxide production is measured from expired air [5]. These measurements are generally made in a laboratory setting, however, portable indirect calorimetry units are available for field measurements. To collect the expired air, a subject must wear a tightly fitting mask over his/her nose and mouth. This is suitable for short term measurements. However, for long duration activities, or for field trials in which subjects must communicate verbally, portable indirect calorimetry is not acceptable and metabolic cost must be measured by other means.

It has been reported that whole body acceleration is correlated to metabolic energy cost [e.g. 1, 3]. Using a triaxial accelerometer mounted over the 2nd lumbar vertebra, Bouten et al. [1] found a significant correlation between accelerometer output and energy expenditure (R = 0.89). They noted, however, that the system underestimated energy cost for some intensive activities (e.g. stepping or carrying loads) and overestimated energy cost for sedentary activities (e.g. sitting, lying and desk work). In a study by Hendelman et al. [3], subjects wore both a uniaxial and a triaxial accelerometer at the level of the hips. It was reported that the relationship between whole body acceleration and energy cost was dependent on the type of activity performed, and that the accelerometer did not detect increased energy cost from upper body movements, load carriage or changes in surface terrain.

The long term goal of this research, is to determine the physiological demand, over several hours, on military personnel participating in field exercises. This is to be done using upper body accelerations, measured using a triaxial accelerometer worn over the sternum[1]. The specific goals of this study are to determine: i) how well the metabolic cost of walking is estimated from upper body accelerations relative to accelerations recorded at the lower back; and ii) whether the measured accelerations are sensitive to changes in metabolic cost due to load carried, changing speed and changing incline.

II. DATA COLLECTION

Fit male subjects were recruited for an experimental study. During the initial session, subjects were asked to fill out a Par-Q questionnaire and to

[1] Accelerometer placement at the level of the lumbar spine or hips would cause unacceptable discomfort, due to the other equipment worn by soldiers.

sign an informed consent form. The experimental protocol was outlined in detail and subjects were encouraged to ask any questions before commencing the study. The subjects' maximum aerobic capacities ($\dot{V}O_{2\max}$) were measured; subjects were required to have a minimum $\dot{V}O_{2\max}$ = 44.5 ml/kg/min. Those subjects accepted for the study were asked to return for four data collection sessions. Sessions were done on separate days, with adequate rest between trials. In each session, subjects completed one of four test batteries, (summarized in Table I), which comprised two 18 minute treadmill walks, while subjects carried one of two loads in the newly designed Canadian Clothe the Soldier (CTS) backpack. Either speed or incline was varied in six minute intervals – this duration was chosen, so that subjects would be in steady state oxygen consumption for at least the last half of the interval.

Table I: Test conditions for the treadmill study; two tests were completed on each experimental day.

Test	Load (kg)	Speed (km/h)	Incline (deg)
A1	0	3.22, 4.83, 6.44	0
A2	38.7	3.22, 4.83, 6.44	0
B1	0	4.83	0, 5, 10
B2	38.7	4.83	0, 5, 10
C1	16.6	3.22, 4.83, 6.44	0
C2	25.9	3.22, 4.83, 6.44	0
D1	16.6	4.83	0, 5, 10
D2	25.9	4.83	0, 5, 10

At the beginning of each session, a Crossbow triaxial accelerometer (model #CXL10LP1) was affixed to the subject's sternum using Skin-Bond®. The accelerometer was oriented such that the y-axis was vertical, the z-axis was in the anteroposterior direction, and the x-axis was in the mediolateral direction. In the zero load condition (test A1 and B1), a second accelerometer was mounted on the lumbar spine of the subject; the axes were in the same planes as described above, but the lumbar accelerometer was rotated 180° about the vertical axis, with respect to the sternum accelerometer. The accelerometer outputs were sampled at 100 Hz and stored.

The subject was also outfitted with a mask that covered his mouth and nose and which was connected to airflow tubes by a high flow pneumotach and plugged into the TEEM 100 metabolic cart. O_2 consumption ($\dot{V}O_2$) and CO_2 production were recorded at 20s intervals.

Eight subjects completed the four test sessions. The mean age of the subjects was 23.6 years (range 21 – 26 years), mean height was 1.8 m (range: 1.69 – 1.85 m) and mean body weight was 78.2 kg (range: 65.4 – 97.07 kg). Out of a total of 64 tests, full data sets were obtained for 47, and partial data sets were obtained for 7 tests.

III. DATA ANALYSIS

The accelerometer and $\dot{V}O_2$ data for analysis were taken from minutes 3-5, 9-11 and 15-17 of each test, when the subject was in steady-state oxygen consumption for the specific test condition. The recorded accelerometer voltages were converted to g's of acceleration and any offset in the data records was removed. The mean rms values for each axis (m_rms_x, m_rms_y and m_rms_z) were computed for the 2 min. intervals. The mean rms magnitude was computed using:

$$m\_rms_{mag} = \sqrt{m\_rms_x^2 + m\_rms_y^2 + m\_rms_z^2} .$$

The power spectral densities (PSD's) of the acceleration records were computed in Matlab®. Total signal power on each axis was computed for each record by integrating the PSD.

III. RESULTS

Analysis of Measured O_2 Consumption

Figure 1 shows a plot of $\dot{V}O_2$, averaged across subjects, versus load carried for changing speed and changing incline.

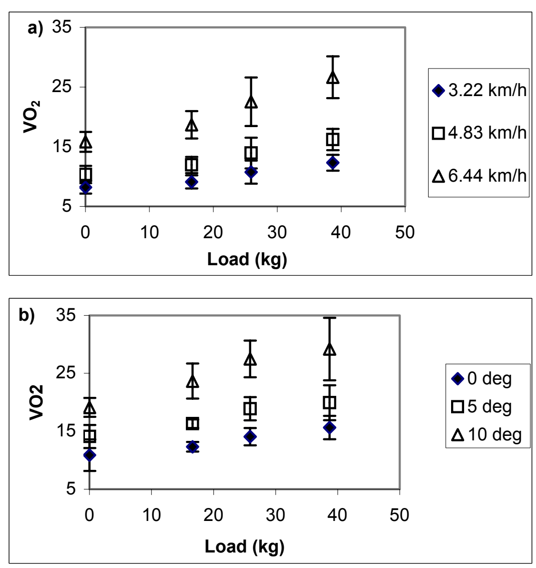

Figure 1: The relationship between $\dot{V}O_2$ and load carried at: a) changing speeds and b) changing inclines. Error bars are ±1 standard deviation.

It is apparent that measured $\dot{V}O_2$ increases with load carried, speed of locomotion and incline. Linear regressions were performed on the averaged data and the resulting values given in Table II. These values show that the slope of the $\dot{V}O_2$ vs load relationship increases with both increasing speed and incline. This indicates that there is an interactive effect between load and speed and load and incline, such that the energy cost associated with load carried increases at a greater rate for higher speeds and inclines.

Table II: Linear regression results for averaged $\dot{V}O_2$ vs load at different speeds and inclines.

Changing speed; incline = 0°			
Speed (km/h)	**Slope**	**Intercept**	**R^2**
3.22	0.11	7.88	0.95
4.83	0.15	10.00	0.97
6.44	0.28	15.16	0.97
Changing incline; speed = 4.83 km/h			
Incline (deg)	**Slope**	**Intercept**	**R^2**
0	0.13	10.68	0.98
5	0.16	14.10	0.97
10	0.27	19.37	0.97

Analysis of Measured Accelerations

Case 1: Zero load

In the zero load tests (A1 and B1), accelerations were recorded at the sternum and over the lumbar spine. A correlation analysis between the accelerometer m_rms values and the measured $\dot{V}O_2$ values was performed in Excel®. The correlation coefficient, R, was calculated as the ratio of the covariance of the m_rms and $\dot{V}O_2$ values divided by the product of their standard deviations. Results of the correlation analysis are given in Table III.

Table III: Correlation coefficients (R-values) between accelerometer rms values and measured $\dot{V}O_2$.

	M_rms_x	**m_rms_y**	**m_rms_z**	**m_rms_{mag}**
Test A1				
Sternum	0.8089	0.9312	0.8981	0.9550
Lumbar	0.8688	0.9571	0.9465	0.9562
Test B1				
Sternum	0.1646	0.7199	0.7904	0.7938
Lumbar	-0.2606	0.4787	0.2707	0.2741

The correlation coefficients are close to 1 for both accelerometers for the case in which energy expenditure is increasing with increasing speed (test A1). For the case of increasing incline, the correlation between accelerations measured at the lumbar spine and increasing energy expenditure is very poor. The correlation is better for accelerations recorded from the sternum.

Case 2: Light, medium or heavy load

The relationship between measured upper body accelerations and load carried, for changing speed of locomotion and changing incline, is less clear than the relationship between $\dot{V}O_2$ and load carried. A representative plot of the magnitude of the mean rms accelerations recorded at the sternum is shown in Figure 2.

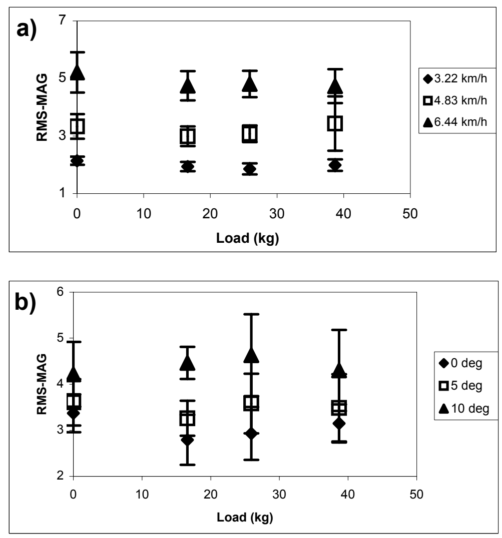

Figure 2: Mean rms magnitude of upper body accelerations vs load carried for a) changing speed and b) changing incline. Error bars are ±1 standard deviation.

The mean rms magnitude of the accelerations does increase with speed and incline, but not with load. This lack of relationship is apparent in other parameters of the acceleration signals.

To determine whether upper body accelerations can be used to predict energy cost, multiple regression analyses were performed where measured $\dot{V}O_2$ was the dependent variable and the independent variables were: load, speed, incline, and the following parameters from the sternum accelerometer: m_rms_x, m_rms_y, m_rms_z, m_rms_{mag}, sp_peak_x, sp_peak_y, sp_peak_z, (the fundamental frequencies of the x-, y- and z-axis accelerations respectively), P_x, P_y, P_z (the spectral power for the x-, y- and z-axis accelerations respectively).

In the first analysis, a statistical model using only load (L), speed (S) and incline (I) as independent variables was derived as the baseline model for prediction of $\dot{V}O_2$. In the 2nd analysis, only the acceleration parameters were used as independent variables and in the 3rd analysis, the acceleration parameters plus load were used as independent variables. The resulting models and R^2 values are summarized in Table IV.

Table IV: Statistical models for prediction of $\dot{V}O_2$

Model	R^2
$\dot{V}O_2 = 4.222 + 1.363(I) + 0.765(S^2) + 0.2(L)$	0.796
$\dot{V}O_2 = 1.438 + 0.146(P_z) - 0.251(P_x) + 0.448(m\_rms_{mag})^2 + 5.733(sp\_peak_y) - 1.105(sp\_peak_z)$	0.604
$\dot{V}O_2 = 5.35 + 0.068(P_z) + 0.191(L) + 0.578(m\_rms_{mag})^2 - 0.148(P_x)$	0.723

IV. DISCUSSION AND CONCLUSIONS

Analysis of measured $\dot{V}O_2$ for conditions of increasing load carried in a backpack, increasing speed of locomotion and increasing incline, verified that each of these factors results in increased energy cost and that $\dot{V}O_2$ can be reliably predicted if all of these factors are known. This is easily accomplished in a laboratory setting, however for field studies or during military training exercises, it is not possible to determine the speed of locomotion and the characteristics of the terrain. The energy costs of the tasks performed must be estimated using other information.

In the study reported here, the use of upper body accelerations to predict $\dot{V}O_2$ for different walking speeds, inclines and loads was evaluated. With no load carried, the rms values of accelerations recorded at both the sternum and the lumbar spine are highly correlated with $\dot{V}O_2$ for increasing speed. For increasing incline, however, the rms values of the sternum accelerations are much better correlated with $\dot{V}O_2$ than the rms values of the lumbar accelerations. This indicates that, for certain tasks, $\dot{V}O_2$ can be better predicted from upper body accelerations, than from accelerations measured at the waist, hips or lumbar spine.

The rms values and spectral power of the upper body accelerations do not increase with increasing load, and thus do not follow the increase in $\dot{V}O_2$. A predictive equation involving acceleration parameters and load carried was derived and found to explain 72.3% of the variance in the data. The ultimate goal is to replace speed and incline (and possibly load) with acceleration parameters in the equation to predict $\dot{V}O_2$. Although the equation derived here explains a reasonable amount of the variation in the data, other acceleration signal parameters may produce better results. Further analysis of the acceleration data is being done.

ACKNOWLEDGEMENT

This work was supported and funded by Defence Research and Development Canada-Toronto; Scientific Authority: Dr. Walter Dyck.

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