META-ANALYSIS TO PREDICT METABOLIC COST AS A FUNCTION OF WALKING SPEED AND ADDED MASS AT DIFFERENT BODY LOCATIONS

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INTRODUCTION

The metabolic cost of carrying an additional mass at different locations on the body relates to many areas, such as ergonomics, the military, obesity, and the design of prosthetic and powered exoskeletons devices. It was found that the most important factors that affect change in energy expenditure are the speed of locomotion [1,2], the magnitude of the additional mass[2], and the location of the additional mass on the body [1,2,3]. It was suggested that metabolic cost increases linearly as the speed increases [4], and that it also increases linearly as the mass carried is increased [2]. However, other researchers depicted these relations as nonlinear [5]. Further, to the best of our knowledge the combined effect of the weight speed has not been studied. Yet for practical applications it is important to be able to predict the metabolic cost for any given combination of speed and mass, which has not been possible from previous studies. Therefore, in this study we aim to model the change in metabolic cost as a function of walking speed and the additional mass, at three body locations: the back, the knee, and the ankle. This has been done by a meta-analysis of previous published studies.

METHODS

To investigate the relations between metabolic cost, speed, and added mass location, we combined data from 14 different studies (back [4,6,7,8,9,10,11,12], knee[2,13,14], and ankle [1,2,15,16]). Note that for the ankle we also used added mass on the foot, for the knee added mass in the lower section of the thigh, and for the back added mass in all of the back locations. All the results reported in the studies were converted to the following units: weight in kg, speed in km/h, and metabolic cost in Watt/kg.
We expected that since the data were gathered from many different studies and labs, there would be differences between the results, even for the same experimental conditions, due to changes in lab equipment. Therefore, there is a need for a model that takes into account two types of variances: within the experiments and between the experiments. Thus, the statistical method of Linear Mixed Model (LMM) was used. The LMM model assumes a linear relation between the dependent variable and the independent variables, and that error **ε** is normally distributed, $\boldsymbol{\varepsilon} \sim N(\mathbf{0}, \boldsymbol{\sigma}^2)$. From our preliminary analyses for the metabolic cost (the dependent variable) and the speed and mass (independent variables), it seems that these assumptions do not hold true. Therefore the Box-Cox power transformation method [17] was used to find a power transformation that changes the relation into a linear one. The mathematical representation after the transformation is:

$$f(y_{ij})=\beta_0+\beta_1*speed_{ij}+\beta_2*weight_{ij}+\beta_3*weight_{ij}*speed_{ij}+\gamma_j+\varepsilon_{ij} \quad (1$$

Where $f(y_{ij})$ is the function that represent the Box-Cox transformation, y is the metabolic cost of the i_{th} measurement of the j_{th} experiment, β_0 is the intercept, $\beta_{1,2,3}$ is the coefficients, γ is the random effect of the j_{th} experiments, and ε is the random error of the i_{th} measurement within the j_{th} experiment.
In order to obtain the equations that best represent the published data from the literature, we applied the above procedure. The ankle data are composed of 16 data points. The added mass and speed ranges were 0-6kg and 3.2-6.4mk/h, respectively. The knee data are composed of 7 data points. The added mass and speed range were 0-2.82kg and 4.5-5.4km/h, respectively. The back data are composed of 67 data points. The added mass and speed range were 0-33.8kg and 2.4-7.2km/h, respectively. The quality of the model was evaluated with R^2 and a 3D graph depicting the metabolic cost equation in relation to the collected data.

RESULTS

The statistical analysis yielded an equation that relates walking speed and added mass at the back, knee, and ankle to the metabolic cost. For all three locations the variance between experiments was 2 to 10 times larger than the variance within experiments. This justifies the choice of the LMM. For the ankle and back the equation's coefficients were found to be significant with the p-value < 0.05. However, for the knee equation the coefficients were marginally significant, with p-values of 0.1, 0.12, and 0.05 for β_0, β_1, β_2, respectively.

The equation for each of the body locations are presented in Table 1. A visual comparison of the models and the data points shows a good fit, with the R^2 values relatively high (Figures 1, 2, and 3).

Table 1: metabolic cost equations for each of the three locations

location	Metabolic cost [W/kg]	#
Ankle	$(0.658+0.306*speed+0.131*weight)^2$	2
Knee	$(0.01-0.002*speed-0.0002*weight)^{-1/3}$	3
Back	$(1.14+0.22*speed+0.021*weight)^2$	4

Note: speed of walking [km/h], and weight [kg].

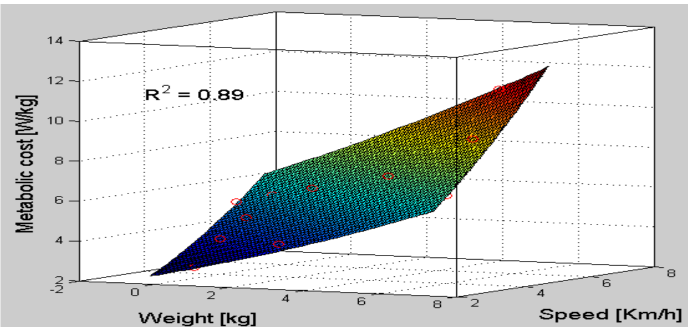

Figure 1: Ankle fitted equation (equation 2) is represents as a plane and the data points are in red

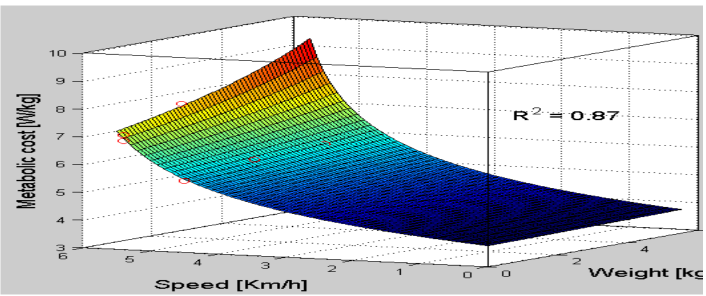

Figure 2: Knee fitted equation (equation 3) is represents as a plane and the data points are in red

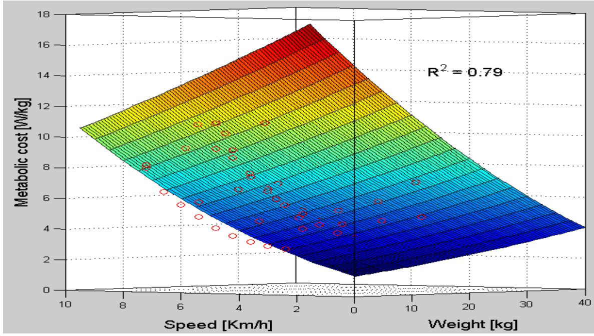

Figure 3: Back fitted equation (equation 4) is represents as a plane and the data points are in red

CONCLUSIONS

In this meta-analysis an LMM and a Box-Cox transformation were used to obtain equations that best describe the changes in metabolic cost as a function of walking speed and added mass, at three different locations (back, knee, and ankle). This is an improvement over previous studies that only consider one factor at a time (i.e., speed or mass). The main limitation of this research: Most of the data is from experiments performed on males, and therefore the accuracy of prediction for females is unknown.

For the knee, there are a small number of data points, and there is a need for more experimental results. The results of this study have many implications for areas such as changes in the metabolic cost of hikers, obesity, and the effect of protective clothing, such as for fire fighters.

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