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Metabolic rate of carrying added mass: A function of walking speed, carried mass and mass location

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The effort of carrying additional mass at different body locations is important in ergonomics and in designing wearable robotics. We investigate the metabolic rate of carrying a load as a function of its mass, its location on the body and the subject's walking speed. Novel metabolic rate prediction equations for walking while carrying loads at the ankle, knees and back were developed based on experiments where subjects walked on a treadmill at 4, 5 or 6 km/h bearing different amounts of added mass (up to 2 kg per leg and 22 kg for back). Compared to previously reported equations, ours are 7–69% more accurate. Results also show that relative cost for carrying a mass at a distal versus a proximal location changes with speed and mass. Contrary to mass carried on the back, mass attached to the leg cannot be modeled as an increase in body mass.

1. Introduction

The level of effort required to carry an additional mass at different locations on the body is important in ergonomics, military applications, obesity and in the design of prosthetics and powered exoskeleton devices. Biomechanical parameters such as ground reaction forces (Birrell et al., 2007; Birrell and Haslam, 2010; Castro et al., 2013), joint kinematics (Attwells et al., 2006; Birrell and Haslam, 2009, 2010; Majumdar et al., 2010; Simpson et al., 2012) and muscle activation using electromyography (Grenier et al., 2012; Knapik et al., 1997) have been used to study load carrying. For example when comparing different methods for carrying the same load, the method that yields lower ground reactions and EMG will be considered better.

While biomechanical parameters can be used for assessing changes in walking, typically the level of effort is considered from a physiological point of view, such as in Simpson et al. (2011) who used heart rate and perceived effort (RPE) as their measurements for the effect of load. Nevertheless, the most common physiological effort is quantified using the metabolic rate which is the amount of energy required by the body to perform an activity (Margaria, 1938). An understanding of how the metabolic rate changes as a function of the additional mass at different walking speeds and body locations is important in designing body armor and protective gear (such as for firemen) since the increase in user effort can limit the use of the gear itself. Furthermore, in the case of assistive technology such as orthopedic braces and active orthosis, the devices, which are performing work during gait cycle, assist the user in restoring locomotion capability. In addition it is preferable that the reduction of the metabolic rate due to the assistance of a particular device be greater than the additional metabolic rate due to the device mass (Collins and Kuo, 2010; Donelan et al., 2008; Sawicki and Ferris 2008).

Previous studies in load carrying have found that the main factor that produces changes in metabolic rate are the speed of locomotion (Bastien et al., 2005; Browning et al., 2007; Soule and

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Goldman, 1969) and the magnitude and location (center of mass) of the additional mass relative to body segments (Browning et al., 2007; Soule and Goldman, 1969; Stuempfle et al., 2004). Metabolic rate is also referred to in the literature as metabolic cost. However, since we are actually measuring metabolic power [w/s], we prefer the use of the term "rate". It was also found that for loading on the lower extremity, the change in the mass distribution (i.e., the moment of inertia) also affects the metabolic rate (Royer and Martin, 2005). It was suggested that metabolic rate increases linearly with mass increase (Bastien et al., 2005; Browning et al., 2007) and speed (Keren et al., 1981). Yet other studies indicate a nonlinear relation between the increase in speed and the metabolic rate (Griffin et al., 2003; Bastien et al., 2005). Abe et al. (2004) and Bastien et al. (2005) studied the cost of carrying a load on the back and depicted nonlinear relations between the metabolic rates for a given mass as a function of the walking speed. This suggests that there is an optimal walking speed for carrying the load.

Pandolf et al. (1977) developed prediction equations for the metabolic rates of walking speed and added mass. Their equations take into consideration body weight, added mass (on the back, hands and ankles), walking speed, surface grade and terrain. Their work was groundbreaking since they were the first to examine the combined effect of all these factors. But their study has two weaknesses: (1) it is not clear how they developed their fitted equation, and (2) they did not specify its prediction error.

The metabolic rate of carrying loads at the knee has not been studied. Yet, the metabolic rate of carrying additional mass at the knee is important for knee braces, prosthetics (Kaufman et al., 2012; Pratt et al., 2004), and for usage as an energy harvester for the knee (Donelan et al., 2008; Riemer et al., 2010). In these devices the additional metabolic rate due to the mass can determine the device's usefulness.

Another important aspect of adding mass at different body locations is the relative metabolic rate of carrying the load. Previously, it was shown that carrying a mass at more distal locations results in higher metabolic rates (Browning et al., 2007; Soule and Goldman, 1969). For example, the net metabolic rate (gross - standing) increases by 8% while walking at 1.25 m/s and carrying 4 kg on the shank compared to carrying the same load on the waist (Browning et al., 2007). The ratio between the metabolic rate of carrying a load on the ankle divided by the metabolic rate of carrying a load on the waist was calculated at a fixed walking speed and added mass. However, it is also important to investigate how the ratio of metabolic rate varies with changes in factors such as speed and mass. In addition it was shown that for mass carried on the back, the effect of the load is similar to an increase in body mass (e.g., Bastien et al., 2005; Goldman and Iampietro, 1962; Legg and Mahanty, 1985). However, it is not known if adding mass at either the ankle or the knee (Browning et al., 2007; Soule and Goldman, 1969) will have a similar effect (such as an increase in body mass).

In our study we investigated the metabolic rate of carrying an added mass as a function of the walking speed, the magnitude of the added mass and its location. We then analyzed the metabolic rates of subjects walking with masses placed on the ankles, knees and backs. Using the results derived from our experiments, we developed an equation to predict the metabolic rate of carrying mass at ankle, knee and back. To the best of our knowledge, an analysis of the metabolic rates of masses placed on the knee has never been carried out before. Then we compared our equations to existing prediction equations (e.g., ACSM, 2000; Pandolf et al., 1977). In addition to determining the error bound in our predictions, we also investigated the differences in the metabolic rate of carrying a mass at distal vs. proximal locations and how the cost is affected by the walking speed and mass magnitude. Finally, we examined whether adding mass at either the ankle or the knee affects the metabolic rate in a way similar to what would happen if there were an increase in body mass.

2. Method

2.1. Subjects

Eight healthy male students (body mass: 74.88 ± 9.23 kg, height: 178 ± 6.21 cm, age: 26.77 ± 2.65 y; mean ± SD) from Ben-Gurion University participated in this experiment. All test subjects engaged 2–3 times a week in recreational sport; all were instructed to sleep for at least six hours on the night prior to the experiment. They were also instructed not to engage in strenuous physical activity for at least 12 hours prior to the experiment. Nor were they to eat two hours prior to the experiment (Hall et al., 2004). The study was approved by Ben-Gurion University's Human Research Institutional Review Board and all subjects signed an informed consent form.

2.2. Experimental procedure

To investigate the effects of walking speed and load placement on metabolic rate, subjects walked with an additional mass on one location: the ankle, knee or back (the ankle and knee loading are bilateral). For each location of added mass, subjects walked at 4, 5 and 6 km/h with either no added mass (no-load), or different magnitudes of mass for each speed. Table 1 summarizes all the trial conditions that each subject experienced (the total number of trial conditions is 37). All trials were performed on a treadmill (T2100 treadmill, General Electric Healthcare, USA) with a zero gradient. The metabolic rate was measured using an indirect calorimetry system (Quark cpet, COSMED, Milano, Italy) and calculated using standard equations (Brockway, 1987).

To become accustomed to walking on a treadmill while wearing a gas collection mask, each subject performed a preliminary trial at a speed of 6 km/h for 7 min. Then, after at least 5 min of rest, subjects performed a randomly ordered set of trials with different added masses. A set consisted of a specific load condition (e.g., 1 kg on the knee) performed at the different walking speeds (4, 5 or 6 km/h). All trials lasted 7 min to allow for the metabolic rate measurements to reach a steady state. Since for all trials, subjects reached a steady state in less than 4 min, the last 3 min of collected data from each trial were used for analysis.

To avoid fatigue, subjects rested for at least 5 min between trials (Abe et al., 2004; Bastien et al., 2005; Browning et al.,

Table 1
Loading conditions used in the experiment.

Location	Mass [kg]	Speed [km/h]
Back	2, 7.1, 10.1, 16.1, 22.1	4, 5, 6
Ankle	0.5, 1, 2	4, 5, 6
Knee	0.5, 1, 2	4, 5, 6
No-load	0	4, 5, 6

Note. At the ankle and knee, the mass refers to the added mass for each leg. Consequently, 0.5 kg at the ankle means that a person carries 0.5 kg on each leg resulting in a total of 1 kg added mass on the body.

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