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

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ABSTRACT

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.

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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 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

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(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., 2007), and the experiment was divided into 3 sessions of approximately three hours on different days. At each session, the subjects carried the added mass at a different location (i.e., first session, ankle; second session, knee; third session, back), The order of the locations between the subjects was random. Subjects were allowed to drink water during rest periods and eat one small energy bar (70–100 kcal) per session (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.

2007). The limitation of one bar per session was chosen because a bar is approximately equal to the total metabolic rate a subject expended per session.

2.3. Leg and back loading

The load magnitudes for each location were chosen based on relevant applications of added mass to legs such as powered exoskeletons (Sawicki and Ferris, 2008) and biomechanical energy harvesters (Donelan et al., 2008) and a Robo Knee (Pratt et al., 2004). Since these devices range in mass from 0.75 kg to 2 kg, we chose 0.5–2 kg as representative masses. For the back, the maximum load was chosen so that the mass would not be more than 33% of the subject's body mass.

The loads were attached to the body using several methods, depending on the location. On the ankle, the added mass was connected with an ankles strap weight (Energy Gym, Delaware, USA) (Fig. 1A). On the knees, the mass was attached above the kneecap on a knee brace with a mass of 500 g (Trainer, Ossur, Reykjavik, Iceland) (Fig. 1B). This arrangement prevented the mass from slipping during walking. One subject could not fit his knee into brace because he had a large shank and therefore, we did not measure his knee trials. On the back, the mass was placed inside a backpack with a waist strap (Fig. 1C). The back load was constructed from packages of flour (1 kg each) with the backpack being packed from the bottom. The backpack straps were tightened to prevent the packages from moving inside the backpack during walking.

2.4. Data analysis

2.4.1. Metabolic rate

After measuring metabolic rate, the specific power of the subject mass was calculated by dividing the metabolic rate (MetR) during the trial by the subject body mass (MetR/BM). The prediction equations were developed using this parameter. To further study the effect of the mass location during each experiment condition, a subject's average metabolic rate was divided by the average total of the body mass and the load mass (BM + LM). It was thought that if the increase in metabolic rate is linearly related to the increase in mass, then, when normalizing to total mass (BM + LM), the experimental results as a function of speed would collide to one line and remain unaffected by the increase in the load.

2.4.2. Prediction model at each location

Based on the experimental data, our aim was to develop a statistical model to predict the metabolic rate for carrying a mass at different body locations (ankle, knee and back). Since different people with various physical traits performed the experiment, we expected intra-subject variability (variances of the subject's measures) and inter-subject variability (variances between subject's measurements). Therefore, a model that would take into account intra-subject and inter-subject variation was needed. Consequently, we chose to use the linear mixed model (LMM) statistical method, which enables us to calculate both types of variability.

The LMM model assumes a linear relationship between the dependent variable and the independent variables and that the error (ε) is normally distributed, i.e., $\varepsilon \sim N\ (0,\ \sigma^2)$. However, our preliminary analysis for metabolic rate as a function of speed and added mass showed that this assumption does not hold true. Therefore, a log transformation was used to make the relation linear and suitable for the LMM. After the transformation, the mathematical representation of our model is:

$$f\left(y_{ij}\right) = \beta_0 + \beta_1 \times \text{speed}_{ij} + \beta_2 \times \text{mass}_{ij} + \beta_3 \times \text{mass}_{ij} \times \text{speed}_{ij} + \gamma_j + \varepsilon_{ij} \quad (1)$$

where $f(y_{ij})$ is the function that represents the log transformation; y_{ij} is the metabolic rate of the i^{th} measurement condition of the j^{th} subject; and β_0 is the theoretical metabolic rate while standing. However, since our prediction equations were developed based on walking speeds of 4–6 km/h, these equations might not accurately predict the metabolic rate at lower walking speeds or when standing (β_0). Therefore, $\beta_{1,\ 2,\ 3}$ are the model coefficients; γ is the random effect of the j^{th} subject; and ε is the random error of the i^{th} measurement within the j^{th} subject.

The speed variable has units of km/h; the mass is in kg; and all the metabolic rate (y_{ij}) values are in W/kg. The metabolic rate is normalized to the subject's body mass to reduce differences between test subjects due to the variations in their weights. The above method was used to develop a model to predict the metabolic rate of carrying mass on the ankle, knee and back as a function of added mass and speed of walking.

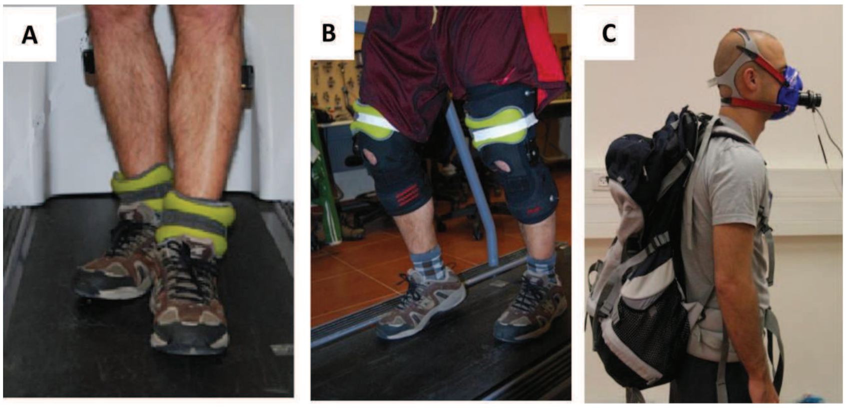

Fig. 1. Loading at different locations: (A) ankle loading with a strap weight (0.5, 1, 2 kg); and (B) knee loading using a knee brace and a strap; (C) back loading using a backpack (2, 7.1, 10.1, 16.1, 22.1 kg).

2.4.3. Relation between the metabolic rate and the body location of the added mass

To study the relative effect of the location of the carried mass, we examined the metabolic rate ratios of walking while carrying loads. This ratio was calculated by dividing the metabolic rate predictions (obtained from Section 2.4.2) of two different body locations. This division provided an equation that predicts the metabolic rate ratio between the locations as a function of the mass and speed of walking. Since we have three different body locations, three different ratios were derived: ankle-knee, ankle-back and knee-back. The equations for the knee and ankle were based on the added mass per leg; for the back, the mass refers to total mass carried on the back. Consequently, an adjustment was needed to compare the same mass magnitudes. Therefore, we multiplied the mass of the back by two to even both equations (e.g., 0.5 kg on the leg equals 1 kg on the back).

2.4.4. Confidence intervals of the predictions

When developing prediction equations based on an experimental fit, it is important to determine the confidence level since this indicates the magnitude of the possible error for each individual's prediction value. The following equation allows us to estimate the range of possible values at a chosen confidence level (Eq. (2)):

$$\text{confidence level}: X_0\widehat{\beta} \pm Z_{1-\alpha/2} \times \sqrt{V_0} \tag{2}$$

where X_0 is a vector of our factor's values (speed and mass); $\widehat{\beta}$ is a vector of the model coefficients; $Z_{1-\alpha/2}$ is the number of standard deviations of the normal standard distribution; and V_0 is the model variance. V_0 is composed of three different sub-variances that cause noise in the model: subjects (within intra-subject variability), error measures (between inter-subject variability) and estimated coefficient errors.

Calculation of the possible error is achieved with the following equation:

$$\text{error} = Z_{1-\alpha/2} \times \sqrt{V_0} \tag{3}$$

$$V_0 = V(\text{between}) + V(\text{within}) + V(\text{coefficients}) \tag{4}$$

V(between) is the variance between subjects, which is the noise due to different subjects with different physical traits. V(within) is the variance within subjects, which is the noise due to different measurements. V(coefficients) is the variance of coefficient estimation.

2.4.5. Comparing our prediction equations to previous prediction equations

To evaluate the accuracy of our prediction equation as compared to previously published prediction equations, all the predictions were compared to published results from other studies (Abe et al., 2004; Browning et al., 2007; Duggan and Haisman, 1992; Legg et al., 1992; Soule and Goldman, 1969). To create uniformity, all metabolic rates measurement reported in these studies were converted to W/kg. To evaluate our new prediction equations, we considered three existing equations and compared their no-load (i.e., walking without load) predictive capabilities to our equations (ACSM, 2000; Pandolf et al., 1977; van der Walt and Wyndham, 1973). Note that Pandolf's equation was used with no-load on the back and a zero grade and terrain factor for a treadmill experiment. We compared our prediction accuracy of load carrying on the ankle and the back to Pandolf's prediction accuracy where each experimental data record contains the walking speed, measured metabolic rate and the added mass. The mean square error (RMSE) was then calculated for each prediction equation. The lower the RMSE, the more accurate the prediction was considered to be.

3. Results

3.1. Equations for prediction of the metabolic rate

The relation between the metabolic rate and speed and added mass (Eq. (5)) has the following form:

$$\text{Metabolic cost} = \text{Exp}(\beta_0 + \beta_1 \times \text{speed} + \beta_2 \times \text{weight} + \beta_3 \times \text{weight} \times \text{speed}) \tag{5}$$

where β_0 theoretically represents the cost of standing with no load; β_1 is the coefficient of speed; β_2 is the coefficient of weight; and β_3 is the coefficient of the effect due to interactions between speed and weight. In all the three load conditions, the interaction between weight and speed after log transformation was insignificant ($p > 0.05$), and the prediction equation for metabolic rate (Eq. (6)) takes the following form:

$$\text{Metabolic cost} = \text{Exp}(\beta_0 + \beta_1 \times \text{speed} + \beta_2 \times \text{weight}) \tag{6}$$

The fitted equations, using the log transformation method, for each body location resulted in a significant R^2 value of 0.78, 0.83, 0.85 for the ankle, knee and back, respectively (P-value <0.05). The variability among the subjects was similar in magnitude to the variability within subjects (Table 2).

Although after log transformation the interactions between the independent variables (speed and weight) were not statistically significant in all three equations (ankle, knee and back), it should be noted that in the prediction equation (Table 2), there is still a multiplication connection between the independent variables (speed and weight). Therefore, there is still an interaction between mass and speed in determining the metabolic rate. Finally, the constant for standing with no load (β_0) is similar but unequal for all 3 locations.

The metabolic rate during walking increased with load magnitude and speed (Figs. 2A and B; 3A and B; 4A and B). In addition, the visual representation of the equation and experimental data show a good fit. For the "Back", the metabolic rate divided by total mass (body and load mass) is only affected by the walking speed (Fig. 2C and D) and not by the load. For the "Knee" and "Ankle", dividing the metabolic rate by total mass reduces the difference between the load conditions, but there is still an increase in the metabolic rate divided by total mass (Figs. 3 and 4C and D).

3.2. Confidence intervals of the prediction equations

The confidence intervals were calculated for all three equations. The interval size changes as walking speed increases and mass is added. However, the size of the confidence intervals relative to the values of the prediction equations remains similar. Tables 3 and 4 present the possible error in the prediction equations for a

Table 2
Metabolic rate predictions are based on the subject's body mass, walking speed, and load location.

Location	Equation	R^2	V_{between}	V_{within}	*P*-value
Ankle	Exp(0.679 + 0.190 × speed + 0.075 × mass)	0.78	0.004	0.005	<0.001
Knee	Exp(0.59 + 0.206 × speed + 0.059 × mass)	0.83	0.004	0.002	<0.001
Back	Exp(0.51 + 0.22 × speed + 0.011 x mass)	0.85	0.003	0.004	<0.001

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

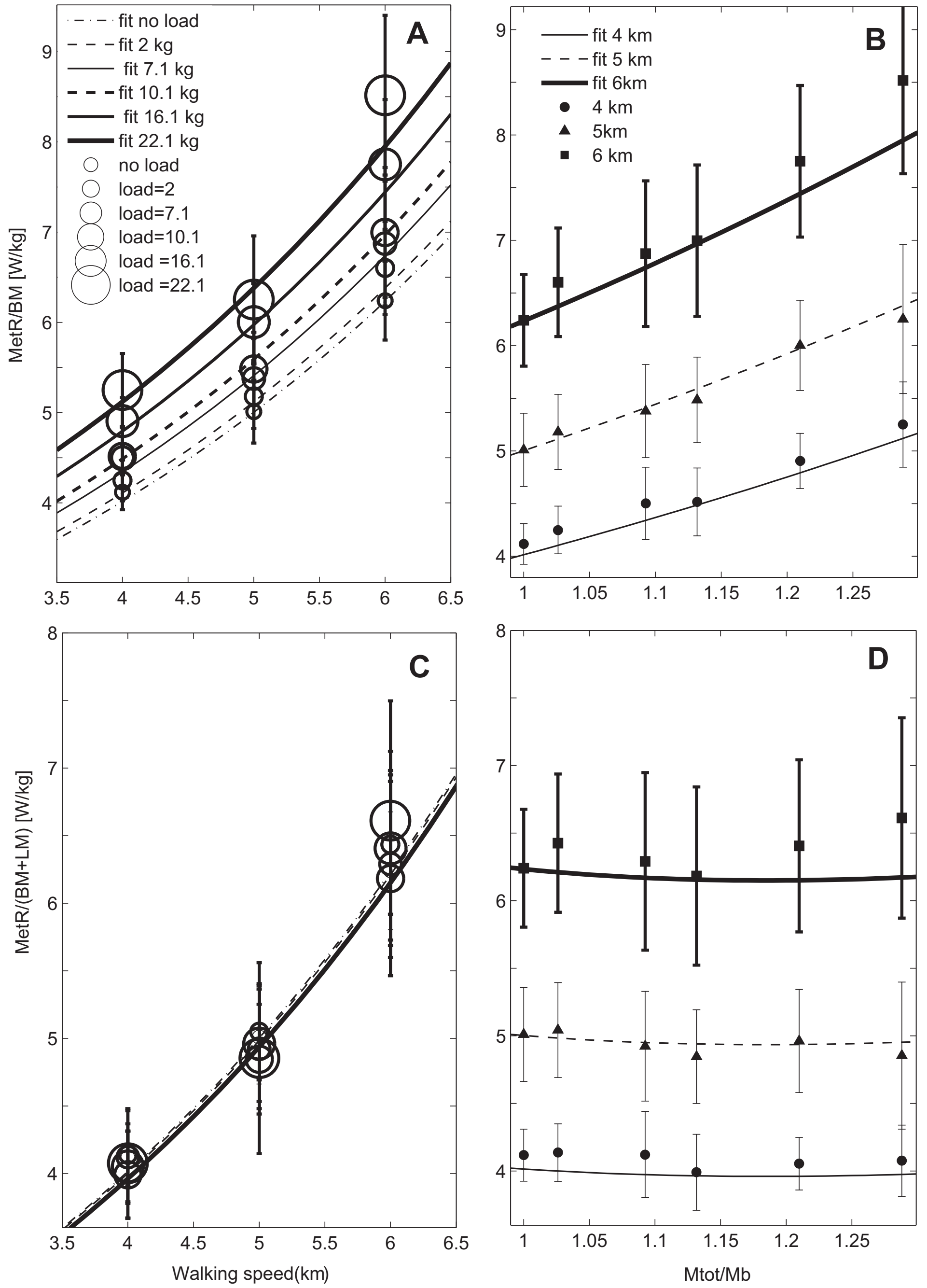

Fig. 2. Back loading effect of load and walking speed on metabolic rate. (A) Metabolic rate (MetR) divided by the body mass (BM) as a function of walking speed. (B) Metabolic rate divided by the body mass as a function of the mass load in unit of total mass (Mtotal) divided by body mass (Mb). (C) Metabolic rate divided by the total mass (body mass and load mass) as a function of walking speed. (D) Metabolic rate divided by the total mass as function of the mass load in unit of total mass (Mtotal) divided by body mass (Mb).

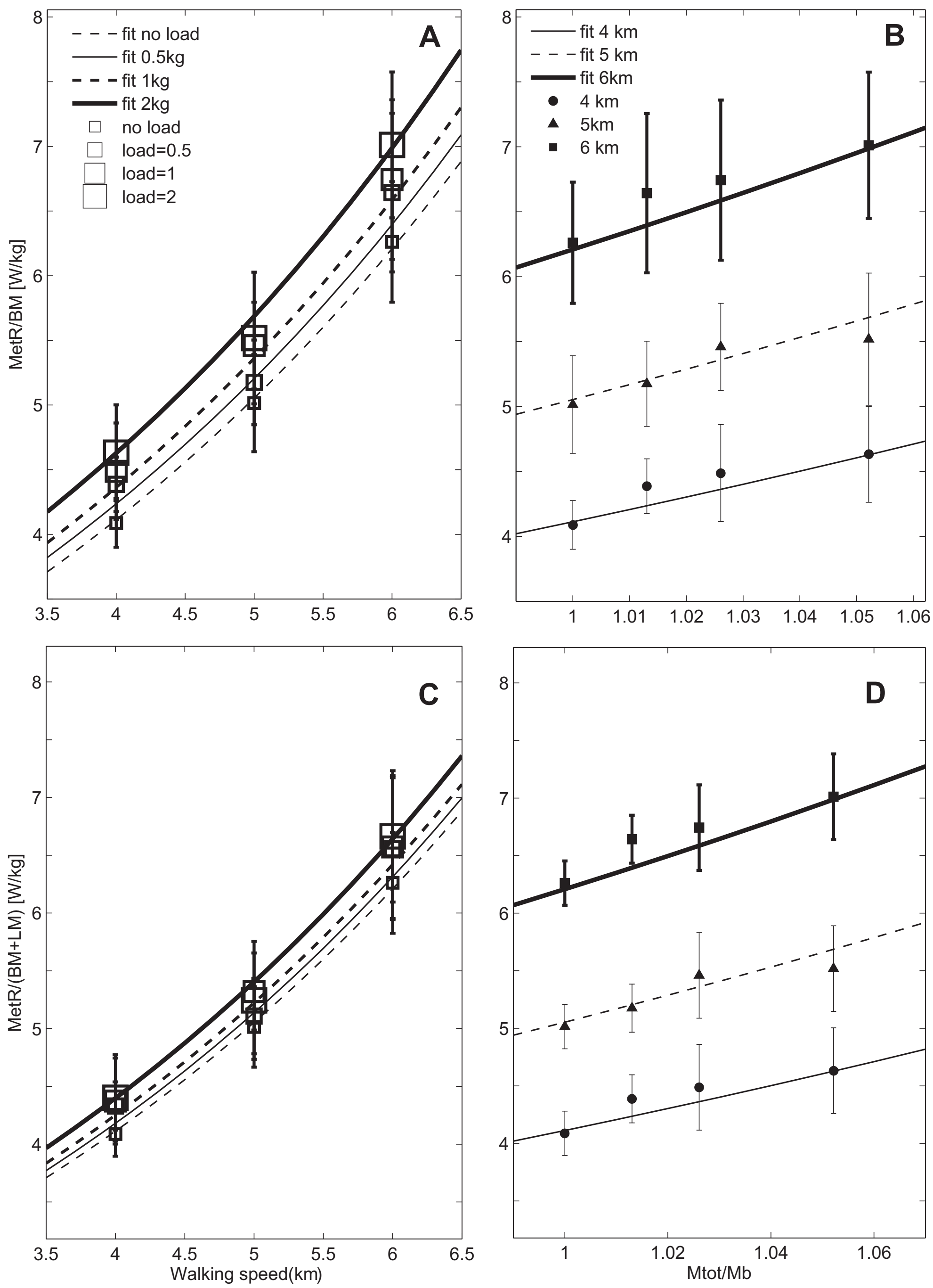

Fig. 3. Knee loading effect of load and walking speed on metabolic rate. (A) Metabolic rate (MetR) divided by the body mass (BM) as a function of walking speed. (B) Metabolic rate divided by the body mass as a function of the mass load in unit of total mass (Mtotal) divided by body mass (Mb). (C) Metabolic rate divided by the total mass (body mass and load mass) as a function of walking speed. (D) Metabolic rate divided by the total mass as function of the mass load in a unit of total mass (Mtotal) divided by body mass (Mb).

confidence level of 95% for several combinations of mass and speed. This means that 95% of the population will be in range of the prediction value +/− a possible error.

In addition, analysis of the confidence level for each of our equations shows that for the ankle prediction, 95% of the results fall within ± of 20%; for the knee, within ±17%; and for the back, within ±17% of the nominal value (value obtained from the equation for a given condition). How to calculate the error for a given mass, walking speed and location on the body is presented in the Appendix.

3.3. Metabolic rate ratio between the locations

After determining the metabolic rate of carrying a load at each of the three locations, we investigated the relative effort between the three locations by dividing the prediction equation for one location by the equation for a different location (e.g., knee by back). All three ratios resulted in an exponential equation (Table 5).

Our findings show that metabolic rate is higher when masses are located more distally and that the ratio between the metabolic rates for carrying loads at different locations changes

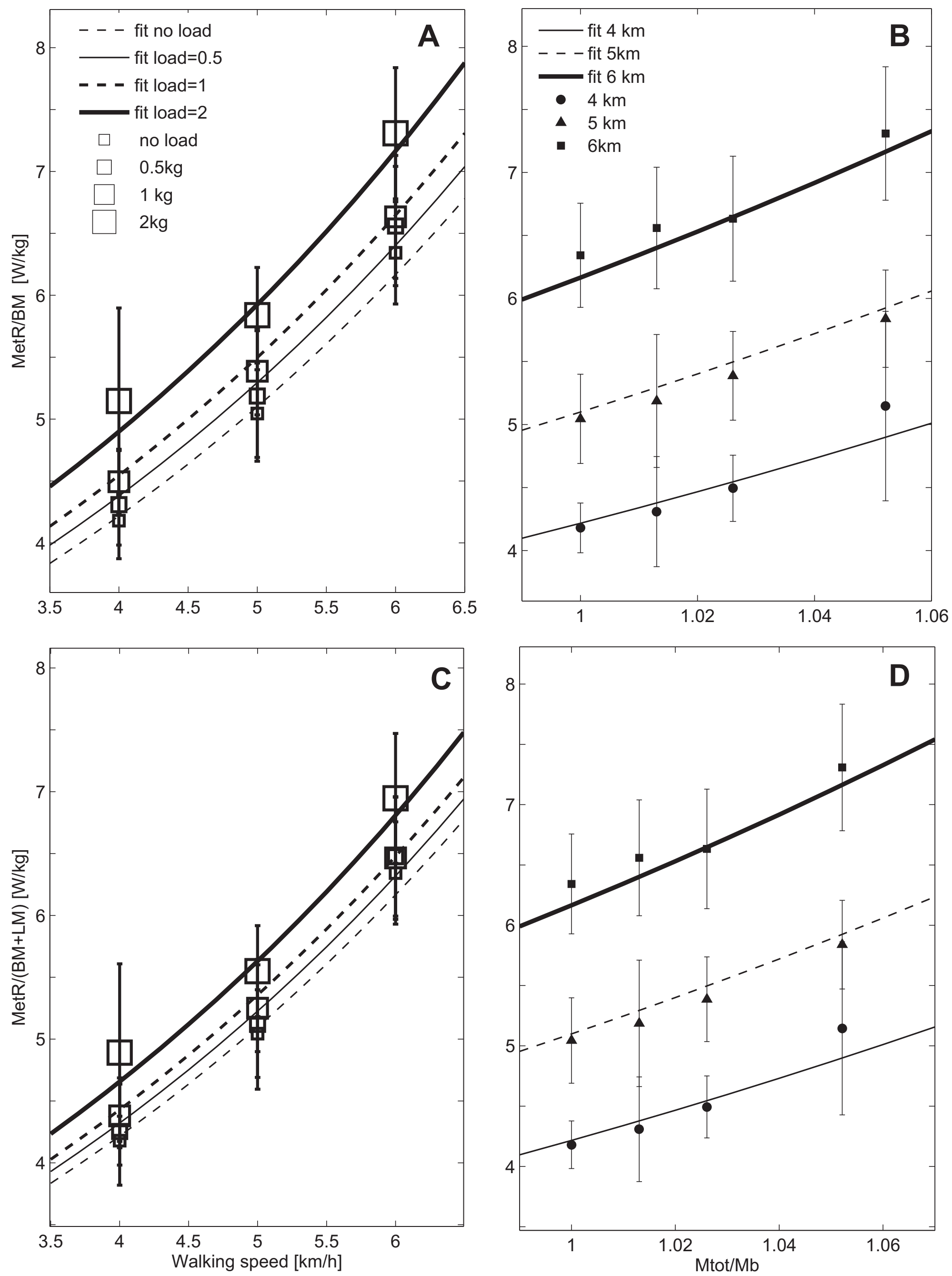

Fig. 4. Ankle loading effect of load and walking speed on metabolic rate. (A) Metabolic rate (MetR) divided by the body mass (BM) as a function of walking speed. (B) Metabolic rate divided by the body mass as a function of the mass load in unit of total mass (Mtotal) divided by body mass (Mb). (C) Metabolic rate divided by the total mass (body mass and load mass) as a function of walking speed. (D) Metabolic rate divided by the total mass as function of the mass load in unit of total mass (Mtotal) divided by body mass (Mb).

(Figs. 5A, 3B, 3C). For the lower walking speeds and higher masses, the ratio between the distal and the proximal location was the highest. For the ankle divided by the knee, the lowest ratio was 0.99 at a walking speed of 6 km/h and with 1 kg total for both legs. The highest ratio was 1.049 at a walking speed of 4 km/h and with 4 kg total for both legs (Fig. 5A). For the knee divided by back, the lowest ratio was 1.015 at a walking speed of 6 km/h and with 1 kg; the highest ratio was 1.103 at a walking speed of 4 km/h and with 4 kg on each leg (Fig. 5B). For the ankle divided by back, the lowest ratio was 1.016 at a walking speed of 6 km/h and with 1 kg of added mass; the highest ratio was 1.167 at a walking speed of 4 km/h and with 4 kg of added mass (Fig. 5C).

3.4. Evaluation and comparison with other prediction equations

Using our prediction equations and data from previously published experiments (Abe et al., 2004; Browning et al., 2007; Duggan and Haisman, 1992; Legg et al., 1992; Soule and Goldman, 1969), prediction errors (RMSE) were calculated. Then, the RMSE was evaluated in relation to other previously published prediction equations. This procedure was performed

Table 3
Back loading metabolic predictions and an interval size of a 95% confidence level, at 9 different points that represent the data. Each point is defined by the mass and walking speed.

Mass [kg]	5	10	15	5	10	15	5	10	15
Speed [km/h]	4	4	4	5	5	5	6	6	6
Prediction Back [W/kg]	4.24	4.48	4.73	5.28	5.58	5.9	6.58	6.95	7.35
Possible error [W/kg]	0.74	0.78	0.83	0.92	0.97	1.03	1.14	1.22	1.29

Table 4
Ankle and knee loading metabolic predictions and at an interval size of 95% confidence level, at 9 different points that represent the data. Each point is defined by the mass and walking speed.

Mass [kg]	0.5	1	2	0.5	1	2	0.5	1	2
Speed [km/h]	4	4	4	5	5	5	6	6	6
Prediction Ankle [W/kg]	4.37	4.54	4.89	5.29	5.49	5.92	6.4	6.64	7.16
Possible error [W/kg] (Ankle)	0.89	0.92	0.99	1.07	1.11	1.2	1.3	1.35	1.45
Prediction Knee [W/kg]	4.23	4.36	4.62	5.2	5.36	5.68	6.39	6.58	6.98
Possible error [W/kg] (Knee)	0.72	0.75	0.79	0.89	0.91	0.97	1.1	1.13	1.2

for walking with no-load (Fig. 6, Table 6) and for load conditions on the ankle and back (Table 6). In all cases, our prediction equations resulted in a smaller RMSE for both no-load and load conditions (Table 6).

4. Discussion

In our study, we investigated the metabolic rate of carrying a mass at three different locations (ankle, knee, and back) as a function of walking speed and added mass magnitudes. An understanding of the metabolic rate is important in designing body armor and protective gear (such as for firemen). Using our results, designers can model the changes in metabolic rate as a function of the mass and their location. They can then use this information to formulate a design criterion (e.g., the addition of metabolic rate should not exceed 15% of a no-load condition).

The new prediction equations that we developed for walking with no-load and walking with a load on the back and ankle were more accurate than previously developed equations, as shown by a relative reduction in RMSE of ~7% for the no-load condition (i.e., Pandolf's equations vs. ours). While the equations of both Pandolf et al. (1977) and van der Walt and Wyndham (1973) demonstrate similar behavior to our predictions and to the data from published literature, the ACSM (2000) prediction equation is a linear curve that does not follow well the published data particularly for velocities above 5.5 km/h . For the ankle and back, the proposed prediction equations are more accurate than Pandolf's with a lower RMSE of 69% for the ankle and 31% for the back.

Table 5
Metabolic ratio of carrying a mass at different body locations.

Area	Equation
Ankle/knee	Exp(0.08 + 0.016 × mass − 0.016 × speed)
Knee/back	Exp(0.08 + 0.037 × mass − 0.014 × speed)
Ankle/back	Exp(0.169 + 0.053 × mass − 0.03 × speed)

Note that the mass in the equations is considered as the mass on one leg (e.g., 1 g per knee).

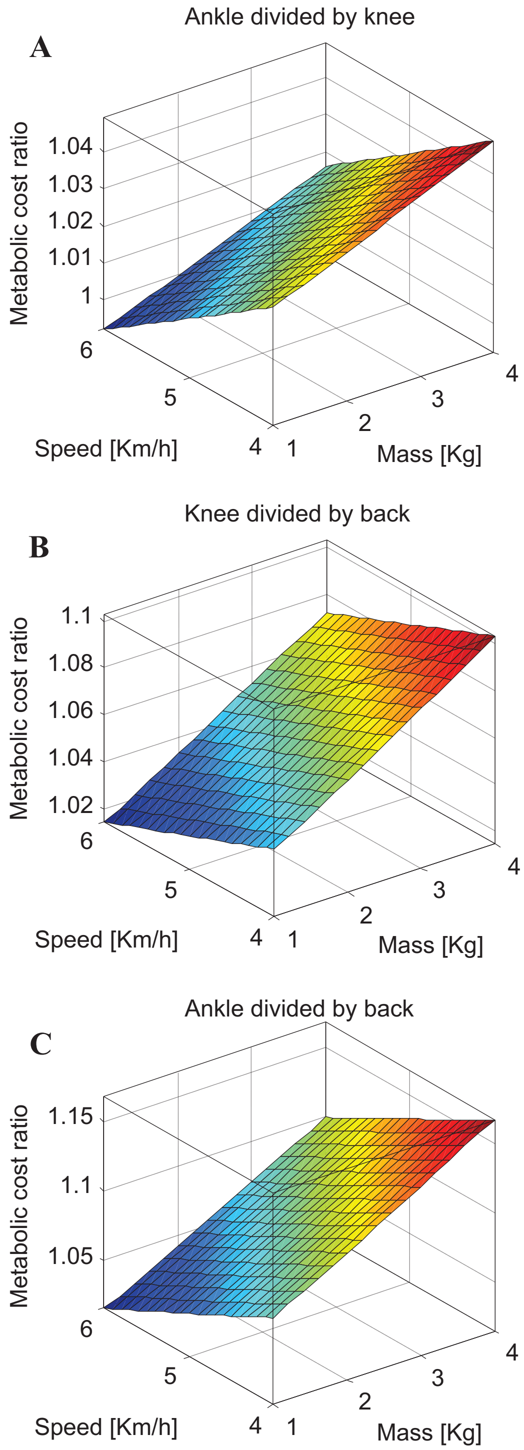

Fig. 5. Ratio of the metabolic rate for carrying the mass at different locations as a function of speed and mass. (A) Ankle divided by knee; (B) knee divided by back; (C) ankle divided by back. Note the mass is presented as the total for both legs. However, in the equation, the mass per one leg is entered.

Prediction equations that are based on an experimental fit are typically best applied only in the range for which the experimental data was obtained. However, the metabolic rate prediction model that was developed in this study obtained better results even for other data in which the conditions were outside the range of values used in our experiments (walking speed range of 4–6 km/h), for

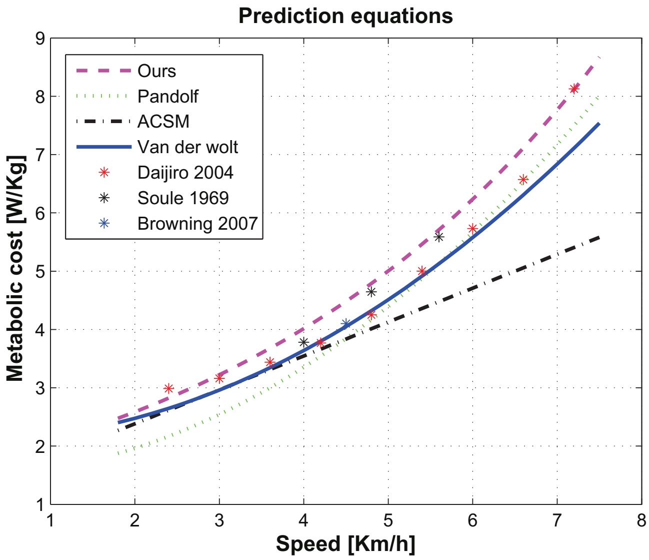

Fig. 6. Evaluation of prediction equations during walking with no load (ACSM, 2000; Pandolf et al., 1977; van der Walt and Wyndham, 1973) vs. experimental results.

example, when walking at a speed of 2 km/h and 7 km/h in the no-load condition. This suggests that, the developed model might be a better representation of the physiological process of load carrying. However, this must be tested in future experiments with lower and higher walking velocities.

Previous studies have shown that when carrying a mass close to the trunk, the metabolic rate increases linearly with the load (Bastien et al., 2005; Goldman and Iampietro, 1962; Legg and Mahanty, 1985). This is similar to an increase in metabolic rate due to an increase in body mass (Bastien et al., 2005; Goldman and Iampietro, 1962; Legg and Mahanty, 1985). These results are similar to our findings and support the methods that approximate the metabolic rate of human locomotion based on motion of the center of mass and total body mass (e.g., Alexander, 1995). Furthermore, carrying a mass at a more distal body location results in a higher metabolic rate relative to a more proximal location (Browning et al., 2007; Soule and Goldman, 1969). However, no previous study has investigated how this ratio changes as a function of walking speed and added mass. Our findings show that as opposed to adding mass close to the trunk, the addition of the mass on the ankle and knee caused a nonlinear increase in the metabolic rate relative to the total mass (BM + LM). Moreover, results show that metabolic rate ratio is larger when the distal location is divided by the proximal location for low walking speeds with large amounts of carried

Table 6
Comparison of the different prediction methods and experimental results from the literature presented as the RMSE.

Loading condition	Equations			
	Ours	Pandolf	ACSM	van der Walt
No-load [W/kg][a]	0.38	0.41	0.99	0.59
Ankle loading [W/kg][b]	0.81	2.6	–	–
Back loading [W/kg][c]	0.798	1.16	–	–

[a] The number of data points of the no load condition is 13 (3 different papers, Abe et al., 2004; Browning et al., 2007; Soule and Goldman, 1969).
[b] Ankle-loading conditions have 25 data points (2 different papers; Abe et al., 2004; Browning et al., 2007).
[c] Back-loading conditions have 30 data points (4 different papers; Abe et al., 2004, Browning et al., 2007; Duggan and Haisman, 1992; and Legg et al., 1992).

mass. However, it is smaller for fast walking speeds and lower added mass.

We believe this effect might be explained by changes in the work being carried out by the body's joints and the ratio of net negative work to net positive work performed at the joints. With a model (Margaria, 1968) that describes the influence of muscle work on the metabolic energy cost of movement:

$$\text{metabolic energy}[J] = \frac{\text{positive work}[J]}{\eta^{+}} + \frac{\text{negative work}[J]}{\eta^{-}} \quad (7)$$

where the metabolic energy is in joules; η^{+} is the muscle efficiency during positive work; and η^{-} is the muscle efficiency during negative work.

Using the above model and data published on the total mechanical work done at the leg joint when walking at different velocities (Farris and Sawicki, 2012) it can be shown that in some cases changes in the ratio of the positive and negative mechanical work performed at the joint level could cause an effect similar to that observed when a load is being carried at distal locations (Fig. 5), e.g., a reduction in the carrying metabolic ratio between the ankle divided by back as the walking speed increases. Moreover, we believe that most of the changes in the joint work will occur during the swing phase since it was shown using sensitivity analysis that an error in estimating the leg segment mass changes the calculation of the torques of the joints mostly during the swing phase (Riemer et al., 2008). This effect is the same as the changes in the joint torques due to attaching the mass to the leg. However, in this study, we did not collect kinetic or kinematic data due to the limitations of our laboratory equipment and therefore, future work is required to investigate this topic.

The limitations of this study are that the equations were developed using results from walking at approximately 2-h periods. However, some studies have shown that a load carried at constant speed for more than two hours results in an increase in metabolic rate (Epstein et al., 1988; Patton et al., 1991). Other studies have shown that there was no increase for fit individuals (VO2 max = 65 ml kg^{-1} min^{-1}) walking under similar load conditions for four hours using a back load that is supported both by shoulder and waist straps (Sagiv et al., 1994). Another issue is that our predictions were based on walking on a treadmill and there is a degree of uncertainty regarding the prediction validity for level walking for locations other than a treadmill. Previous studies presented conflicting results when comparing walking on a treadmill with walking on a level ground track: Hall et al. (2004) found no differences while Pearce et al. (1983) found statistically significant differences. However, in the latter study, the differences were smaller than 7%. Since we found that the prediction error for a given individual can be as high as 20%, the difference between the ground and the treadmill metabolic rate might not actually be so important as it is in the prediction error of the equations. Therefore, our equations may be useful in predicting ground level walking outside the lab. Future work should examine whether there is a difference between walking on a treadmill and walking on level ground and develop similar prediction equations for inclined and declined walking.

Lastly, we think that in addition to providing information for able-bodied subjects, our prediction equations could have an impact in the field of rehabilitation for the design of orthotics and other wearable assistive devices. However, people with gait disorders have different gait mechanics (kinematics, kinetics) and metabolic rates than the normal population. Therefore, there is a question of whether the results can be extended to populations with gait disorders. We believe that in the cases where the assistive device restores the gait mechanics to close to normal, the changes in the metabolic rate due to the addition of the mass will be similar to that of able-bodied subjects. However this requires more investigation of the gait disorder pollution, since what might be true for some disorders may not be true for others.

In regard to improving the prediction equations of the metabolic rate, in this study we aimed for a model that would be as generalized as possible. Consequently, our prediction results were R^2 in the range 0.78–0.85. These predictions might be improved by considering individual characteristic such as a self-selected walking pace, level of aerobic endurance fitness (VO2 max), adaption (is the subject used to carrying a load?) height, age, and more. All these factors should be considered in future studies.

5. Conclusions

This study investigated the metabolic rate of human subjects as a function of speed and load when walking and carrying different loads on the ankle, knee and back. We used a linear mixed model (LMM) with a log transformation to formulate our prediction equations. (This is the first time in the literature that a prediction equation has been presented for the knee,). Comparison between our new equations to the best previously reported method (Pandolf et al., 1977) show improvement in accuracy.

Further results show that contrary to mass carried on the back, mass attached to the leg cannot be modeled as an increase in body mass. Anther finding is that the ratio for metabolic rate required for carrying a mass at different location (e.g. back vs. ankle) changes as a function of walking speed and mass and should not be treated as a fixed number. In brief, this study contributes to our understanding of load carrying and has implications in the design of devices that attach to the human body, such as shoes, orthopedic braces, powered exoskeletons and body armor.

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Appendix

Calculating the possible error in our prediction equations (with a confidence level of 95%) for any given combinations of mass and speed:

$$\text{error} = Z_{1-\alpha/2} \times \sqrt{V_0} \tag{A1}$$

$$V_0 = V(\text{between}) + V(\text{within}) + V(\text{coefficients}) \tag{A2}$$

where $V(\text{between}) + V(\text{within})$ and their values are presented in Table 2 For all body locations.

$$V(\text{coefficient}) = \begin{pmatrix} 1 & \text{speed} & \text{mass} \end{pmatrix} \times \begin{pmatrix} \text{cov(intercept, intercept)} & \text{cov(intercept, speed)} & \text{cov(intercept, mass)} \\ \text{cov(speed, intercept)} & \text{cov(speed, speed)} & \text{cov(speed, mass)} \\ \text{cov(mass, intercept)} & \text{cov(mass, speed)} & \text{cov(mass, mass)} \end{pmatrix} \times \begin{pmatrix} 1 \\ \text{speed} \\ \text{mass} \end{pmatrix}$$

In the first and last vectors, speed and mass represent the selected current values. Because the intercept is constant, it is multiplied by 1. The middle vector is the covariance vector of the estimated coefficients. For each body location, there is a different covariance vector.

$$\text{Ankle}: \begin{pmatrix} 0.0024 & -3.616e-4 & -3.85e-5 \\ -3.616e-4 & 7.23e-5 & -1.95e-20 \\ -3.85e-5 & -1.95e-20 & 2.204e-5 \end{pmatrix}$$

$$\text{Knee}: \begin{pmatrix} 0.0013 & -1.223e-4 & -1.63e-5 \\ -1.223e-4 & 2.446e-5 & -4.13e-22 \\ -1.63e-5 & -4.13e-22 & 8.153e-6 \end{pmatrix}$$

$$\text{Back}: \begin{pmatrix} 0.0014 & -1.99e-4 & -4.29e-6 \\ -1.99e-4 & 3.98e-5 & -2.66e-20 \\ -4.29e-6 & -2.66e-20 & 4.49e-7 \end{pmatrix}$$

Thus, for calculating the model error, we need to choose the walking speed, mass and body location and insert their respective values into Eqs. (A1) and (A2). For example, if we want to determine the error while walking 5 km/h and carrying 0.5 kg on the ankle, we use $V(\text{between}) + V(\text{within})$ of the ankle (as presented in Table 2); for the calculation of $V(\text{coefficient})$, the speed value is 5, the mass value is 0.5, and we use the ankle coefficient covariance matrix. The resulting calculation for the 95% confidence interval is as follows:

$$\text{Error} = Z_{0.975} \times \sqrt{0.0037 + 0.0046 + \begin{pmatrix} 1 & 5 & 0.5 \end{pmatrix} \begin{pmatrix} 0.0024 & -3.616e-4 & -3.85e-5 \\ -3.616e-4 & 7.23e-5 & -1.95e-20 \\ -3.85e-5 & -1.95e-20 & 2.204e-5 \end{pmatrix} \begin{pmatrix} 1 \\ 5 \\ 0.5 \end{pmatrix}} = 1.07\ \text{W/kg}$$

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