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Short communication

A simple model for predicting walking energetics with elastically-suspended backpack

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ABSTRACT

An elastically-suspended backpack offers biomechanical benefits by reducing peak interaction force, joint loads and chances of potential injuries as shown in previous studies. But whether it will reduce metabolic cost of the carrier (compared with the stiffly-attached pack) depends on the relation between the natural frequency of the suspension and walking frequency. Yet, no quantitative method can precisely evaluate to what extent the elasticity of suspension affects human walking energetics. We employ a single degree of freedom (DOF) model to quantitatively evaluate the effect of stiffness and damping of pack on human energetics. A surrogate of metabolic cost is proposed and utilized to estimate the energetics difference between carrying backpacks of different stiffness. The predicted difference is consistent with former backpack studies. The analysis reveals that the energy cost increases around the resonant frequency and the difference gets more significant at higher walking speeds or with heavier loads. This method gives closer energetic estimation compared with previous studies. Yet there is potentially an underestimation of the energy difference indicating later models should contain horizontal motion to obtain more precise prediction.

1. Introduction

Although transportation technology has been much advanced, walking with packs is still inevitable, especially for those hikers, soldiers or students (Knapik et al., 2004; Ren et al., 2005; Rome et al., 2006). One of the most important factors in load carriage is energetics. Less energy consumption means the capability for longer distance and heavier loads (Rome et al., 2006).

Human energetics of load carrying is affected by many factors including load distribution, weight of the load, walking (or running) speed, etc. (Abe et al., 2004). Early researchers mainly focused on the effect of different load-carrying methods including using head-packs, yokes, hands, etc. (Balogun, 1986; Datta and Ramanath, 1971; Ramanath et al., 1972) and load distribution (on back, legs or hands) (Legg and Mahanty, 1985; Obusek et al., 1997; Soule and Goldman, 1969).

Recently, the elasticity of linkage between load and the carrier was explored and it was proved to be able to offer considerable biomechanical benefits by reducing the peak interaction force, joint forces and potential injuries when decreasing the stiffness of backpack linkage (Ren et al., 2005; Rome et al., 2006). A few studies also showed that carrying load elastically can reduce the energy cost of walking. Rome et al. (2006) designed a backpack which cost 6.25% less energy in elastically-suspended mode than that in stiffly-fixed mode. Compliant poles were also found to be more energy-saving than steel poles during walking with load (Castillo et al., 2014). Similarly, a legged robot cost less energy while carrying load with elastic suspension (Ackerman and Seipel, 2013). Foissac et al. (2009), however, found carriers consumed more energy with a flexible backpack than a rigid one when walking at 5.2 Km/h and 6 Km/h. Ren et al. (2005) carried out an simulation of carrying backpack with different stiffness but found that stiffness and damping of backpack had little effect on energetics.

Ackerman and Seipel (2014) employed a two-DOF model to explain the conflict experimental results on energy cost in previous studies (Foissac et al., 2009; Rome et al., 2006). Net mechanical work from the assumed leg actuator in a stride, which was treated as an indirect indicator of energy cost, increased and decreased over 60% when carrying the flexible backpack compared with the work of carrying the rigid pack using parameters in previous experiments by Foissac et al. (2009) and Rome et al. (2006) respectively. However, the energetics difference between

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carrying packs of different stiffness was found less than 10% in previous experiments. There still lacks a method that can accurately estimate the energy cost of carrying load with elastic suspension.

The purpose of this paper is to provide an alternative method to quantitatively evaluate the influence of the elasticity of backpack on human energetics. Horizontal motion is assumed to be unaffected for different suspension and mechanical work on center of mass (COM) was reported to be correlated with the body metabolism (Kramer and Sylvester, 2011). Hereby the mechanical work required by vertical motion is treated as a surrogate of energy cost. Different from the study by Ackerman and Seipel (2014), we take the efficiency of the muscle performing mechanical work into consideration when calculating the energy cost of backpack carriage. It's expected that in this way less discrepancy between the model predictions and energy cost measurements in previous experiments will be obtained.

2. Methods

The single degree-of-freedom (DOF) spring-mass-damper model in Fig. 1 (A) was used to assess the performance of elastically-suspended backpack in the previous study by Hoover and Meguid (2011). The equivalent spring and damper were proved to be effective to characterize the kinematics of the vertical interaction between the carrier and the backpack. The equation of motion of this simple vibration model is:

$$m\ddot{y}+c(\dot{y}-\dot{x})+k(y-x)=0 \tag{1}$$

where x denotes the sinusoidal movement of the body COM, and its amplitude (X) and frequency (ω) both vary with respect to the walking speed and can be calculated with empirical equations (Hoover and Meguid, 2011). And y is the movement of the backpack excited by the motion of body. The stiffness k and damping c are the equivalent spring constant and damping coefficient.

The lower-limb muscles in body work collaboratively to achieve the vertical motion of body COM. The actuating force can be solved with Eq. (2), which is similar with the reaction force of the leg described by Ackerman and Seipel (2014). M and m denote the mass of the carrier and the backpack. $|F_{osc}|$ is the amplitude of the accelerative force of the backpack.

$$F_{leg}=Mg+mg-|F_{osc}|\sin(\omega t-\phi)-MX\omega^2\ \sin(\omega t) \tag{2}$$

The instantaneous net mechanical power derived from muscles in body is calculated as

$$P_{mech}=F_{leg}\cdot\dot{x} \tag{3}$$

Positive work is performed on body COM when the velocity is upward and negative work for downward motion as shown in Fig. 1(C). The net mechanical work in a step period calculated by integrating the instantaneous power in Eq. (3) was used to approximate the energy cost by Ackerman and Seipel (2014). However, the counteraction of the positive and negative work was neglected with their method. Muscles perform positive work with an efficiency of around 25% and negative work at a higher efficiency of −120% (Huang and Kuo, 2014; Margaria, 1976). Thus, we propose a new surrogate of the energy cost taking the efficiency into consideration.

By considering the efficiency (η) of muscles performing mechanical work, the energy cost W_{energy} over one walking cycle is calculated as

$$W_{energy}=\int_{t=0}^{2\pi/\omega}F_{leg}\cdot\dot{x}/\eta dt \quad \eta=\begin{cases}25\% & F_{leg}\cdot\dot{x}>0\\ -120\% & F_{leg}\cdot\dot{x}<0\end{cases} \tag{4}$$

Based on the calculation method above, analyses are carried out under conditions listed in Table 1. Firstly analysis under a typical carriage condition is taken to obtain a comprehensive understanding of the effect of stiffness, damping, mass and walking velocity on energy cost. Then, parameters in experiments by Foissac et al. (2009) and Rome et al. (2006) are used as the input of the model to predict the difference of energy cost between the flexible pack and the rigid pack. The predictive results are then compared with the experimental results to determine the effectiveness of the model.

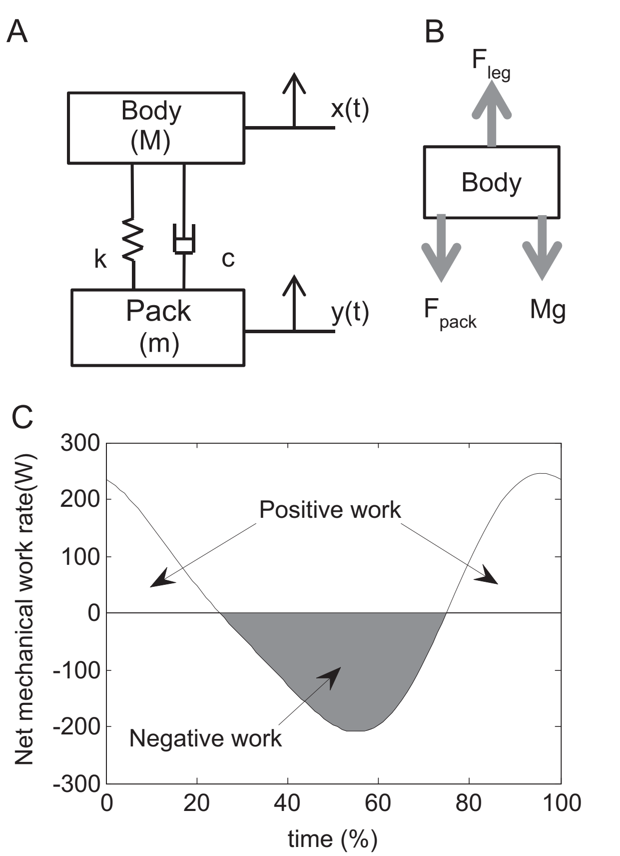

Fig. 1. (A) The spring-mass-damper model to characterize the carrier-backpack system. (B) The free body diagram of the body. (C) The net mechanical work rate of a subject (weight: 74 kg and height: 1.78 m) walking at 5 Km/h with a pack of 18.5 kg. The stiffness k=3300 N/m and damping c=96 Ns/m are the same as those of the flexible backpack in Foissac et al. (2009).

3. Results

The energy cost calculated with the proposed method in this paper presents similar trend with the net mechanical work used by Ackerman and Seipel (2014) but is closer to the actual cost as shown in Fig. 2. The predicted energy cost is in the magnitude of around 200 J, while the net mechanical work is in the magnitude of around 4 J, far less than the real energy cost of human. The energy cost increases when the stiffness is tuned near to the resonant walking frequency and the increase is more significant for lower damping. However, the energy cost difference between different elastic suspensions is modest and less than 10% under most conditions. Fig. 3 indicates that higher mass of load and higher walking speed cost more energy during walking and also will expand the difference between the energy costs of walking under different suspensions.

The predicted energetics difference between the flexible and the rigid backpack with the proposed method is much closer to the experimental results than percentages reported in Ackerman and Seipel (2014) as shown in Table 2. The predicted difference is less than 10%, which agrees with the experiments. However, an underestimation of percentage compared with the actual experimental results can also be seen.

4. Discussion

In this paper, we focused on the influence of the elasticity of backpack suspension on human energetics. The single-DOF model that was used to characterize the mechanical properties of backpack (Foissac et al., 2009) and to evaluate the performance of elastically-suspended pack (Hoover and Meguid, 2011) in former studies was chosen due to its simplicity and effectiveness to characterize the interaction between the pack and the carrier.

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