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Short communication

A model of human walking energetics with an elastically-suspended load

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ABSTRACT

Elastically-suspended loads have been shown to reduce the peak forces acting on the body while walking with a load when the suspension stiffness and damping are minimized. However, it is not well understood how elastically-suspended loads can affect the energetic cost of walking. Prior work shows that elastically suspending a load can yield either an increase or decrease in the energetic cost of human walking, depending primarily on the suspension stiffness, load, and walking speed. It would be useful to have a simple explanation that reconciles apparent differences in existing data. The objective of this paper is to help explain different energetic outcomes found with experimental load suspension backpacks and to systematically investigate the effect of load suspension parameters on the energetic cost of human walking. A simple two-degree-of-freedom model is used to approximate the energetic cost of human walking with a suspended load. The energetic predictions of the model are consistent with existing experimental data and show how the suspension parameters, load mass, and walking speed can affect the energetic cost of walking. In general, the energetic cost of walking with a load is decreased compared to that of a stiffly-attached load when the natural frequency of a load suspension is tuned significantly below the resonant walking frequency. The model also shows that a compliant load suspension is more effective in reducing the energetic cost of walking with low suspension damping, high load mass, and fast walking speed. This simple model could improve our understanding of how elastic load-carrying devices affect the energetic cost of walking with a load.

1. Introduction

Carrying heavy loads can induce significant peak forces on the body and increase the metabolic cost of walking (Abe et al., 2008, 2004; Bastien et al., 2005a; Knapik et al., 2004; Pandolf et al., 1977). Recent evidence has shown that carrying a load with a compliant suspension can reduce the peak forces acting on the body compared with a typical stiffly-attached load. Kram showed that compliant poles used in Asia to carry heavy loads while running can reduce the peak shoulder forces, loading rates, and ground reaction forces (Kram, 1991). Recent studies on walking while carrying a backpack load showed that reducing the suspension stiffness of a backpack could similarly reduce the peak forces acting on the body (Foissac et al., 2009; Hoover and Meguid, 2011; Kuo, 2005; Rahman et al., 2012; Ren et al., 2005; Rome et al., 2005, 2006; Xu, 2009). However, one study shows that the peak forces of the load acting on the body can actually be increased if the natural frequency of the load suspension is tuned near the resonant stride frequency of walking (Foissac et al., 2009). To explain this phenomenon, the dynamics of a load suspension were modeled using a single degree of freedom spring–mass–damper model (Hoover and Meguid, 2011), which described how the peak forces of the load acting on the body could change different suspension stiffness and damping values as well as change pack loads and walking speeds.

Although the dynamics of a suspended load are now well-understood, it is not known how carrying a suspended load can affect the energetic cost of walking. One study predicted via simulation that the stiffness and damping of a backpack suspension will have little effect on human locomotion energetics (Ren et al., 2005). However, another study experimentally showed that walking with a very compliant suspended backpack reduced the energetic cost of walking by 6.2% compared to that of a stiffly-attached backpack (Rome et al., 2006). A different study experimentally showed that a flexible backpack with a stiffness tuned near the resonant frequency of walking had a little effect or slightly increased the metabolic cost of walking relative to a stiffly-attached backpack (Foissac et al., 2009).

The objective of this paper is to resolve and help explain the apparent differences in published data on the energetic cost of

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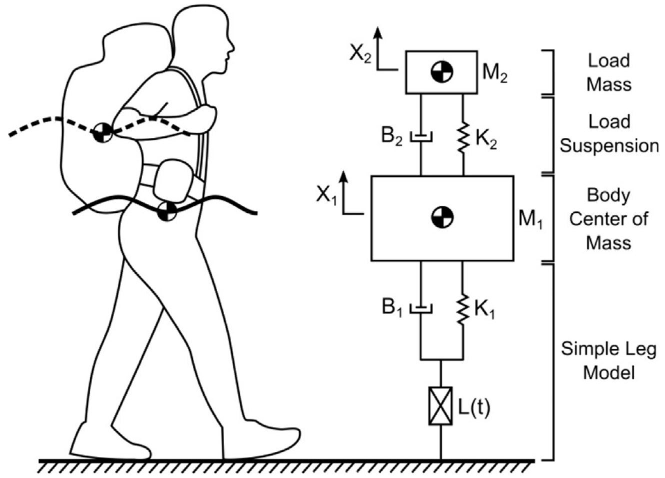

Fig. 1. A simple double-mass coupled-oscillator model can approximate the vertical dynamics of the human body while walking with a load.

walking with a suspended load and to systematically investigate the effect of varying the parameters of a load suspension over a range of physically relevant values. The approach taken is to model human walking with a load suspension as a vertical double-mass coupled-oscillator model (Fig. 1).

2. Methods

The center of mass of the human body during walking has a significant vertical displacement between 3 and 7 cm, depending on locomotion speed (Gard et al., 2004). A stiffly-attached load must undergo a similar displacement during each stride. This induces additional accelerative forces on the body from the load and increases the energetic cost of walking (Bastien et al., 2005b).

Different models have been proposed to study human walking with a suspended load. Ren et al. proposed a whole body, inverse dynamics gait model to study the effect of the suspended load on human walking (Ren et al., 2005). Single degree-of-freedom vibration models have also been proposed to study the vertical dynamics of the suspended load with a given body trajectory as a known input (Foissac et al., 2009; Hoover and Meguid, 2011; Xu, 2009). These models only consider the vertical dynamics of a backpack because the angle of the backpack from the vertical direction is typically small (Kinoshita, 1985). They provide a useful first approximation to study the vertical dynamics of a suspended load.

We developed a vertical double-mass model with coupled load and body masses and an effective spring-leg to investigate the energetics of human walking with a suspended load. This simple model represents a system that vertically oscillates in place by sinusoidally varying the length of the effective spring-leg which is always in contact with the ground (Fig. 1). We have introduced this model previously (Ackerman and Seipel, 2011a, 2011b, 2013), and here present an expansion of our analysis to gain deeper insight into the energetic cost of human walking with a suspended load. The equations of motion for the body mass M_1 and load mass M_2 from static equilibrium are

$$M_1\ddot{X}_1+(B_1+B_2)\dot{X}_1-B_2\dot{X}_2+(K_1+K_2)X_1-K_2X_2=B_1\dot{L}(t)+K_1L(t), \tag{1}$$

$$M_2\ddot{X}_2+B_2\dot{X}_2-B_2\dot{X}_1+K_2X_2-K_2X_1=0. \tag{2}$$

The vertical motion of the center of mass of the human body during walking can be approximated by a sinusoid with a fixed amplitude and frequency (Saunders et al., 1953). In the double-mass model, the sinusoidal leg length function $L(t)$ is used as an actuator to vary the equilibrium length of the spring-leg to achieve motion similar to the vertical center of mass displacement of the human body, where

$$L(t)=A\ \sin(\omega_f t). \tag{3}$$

The frequency ω_f (rad/s) of the human center of mass during locomotion can be approximated as a function of the walking speed v (m/s) and height S (m) (Grieve and Ruth, 1966)

$$\omega_f=\frac{4\pi\times 64.8(v/S)^{0.57}}{60}. \tag{4}$$

We selected the actuator amplitude A (Table 1) through trial and error by comparing the model prediction for the net vertical displacement of the body with an excellent experimental evidence provided by Foissac et al. Though the actuator amplitude may vary with speed (Foissac et al., 2009), we found good agreement with the experimental data by using a constant A value for all walking speeds.

The instantaneous mechanical power output of the leg actuator is approximated by multiplying the reaction force of the leg on the body mass M_1 with the velocity v of the leg length forcing $\dot{L}(t)$, where

$$F_R=K_1(X_1-A\ \sin(\omega_f t))+B_1(\dot{X}_1-\omega_f A\ \cos(\omega_f t))+(M_1+M_2)g, \tag{5}$$

$$P=F_R v=F_R(\omega_f A\ \cos(\omega_f t)). \tag{6}$$

Table 1
Parameters for the double-mass coupled-oscillator model used to approximate human walking with a load. We assume that the effective leg stiffness and damping values predicted by Zhang et al. applies to human walking with a variable stiffness pack load. These effective leg stiffness and damping values are estimated by moving the human body vertically with a harness and fitting the approximate center of mass motion to a simple spring–mass–damper system (Zhang et al., 2000). Since an experimental approximation of the effective leg stiffness and damping during human walking with variable load suspensions is currently unavailable, we choose to use the values from Zhang et al. as the closest experimentally-derived approximation of the effective properties of the human leg in the vertical direction. These values are assumed to be constant in this study. New knowledge regarding the variability of these effective leg parameters versus changing walking phases, speeds, and load conditions may result in increasingly higher fidelity modeling.

Parameter	Description	Value
S	Body height (Foissac et al., 2009)	1.791 m
K_1	Effective leg stiffness (Zhang et al., 2000)	28,500 N/m
B_1	Effective leg damping (Zhang et al., 2000)	950 N s/m
M_1	Body mass (Foissac et al., 2009)	74 kg
K_2	Suspension stiffness	Variable (Table 2)
B_2	Suspension damping	Variable (Table 2)
M_2	Load mass	Variable
v	Walking speed	Variable
ω_f	Locomotion frequency	Variable (Eq. 4)
A	Leg actuator oscillation amplitude	0.01 m
g	Gravity	9.8 m/s^2

Table 2
Effective parameters for the flexible and suspended backpacks developed by Foissac et al. and Rome et al. Foissac et al. measured the stiffness and damping of their load suspension using two separate techniques (Foissac et al., 2009). In the first technique, the force impulse response of the leaf spring suspension itself without the backpack link is measured with an accelerometer and the data is fitted to the spring–mass–damper system. In the second technique, the dynamic response of a human subject wearing each backpack is fitted to another spring–mass–damper model. The dynamic response from the human subject data with the suspension and the backpack link interface with the body significantly reduce the effective stiffness and increase the effective damping of both the stiff and flexible suspensions. The differences in the results of these two methods provide some uncertainty in the parameters, particularly regarding how to define the stiffly-attached backpack load, which is used as a benchmark for comparison. However, in this study we choose to use the mean stiff backpack and flexible backpack parameters. We also choose to use the mean stiff backpack parameters as a benchmark for comparison against all suspended loads because these parameters are the best representation of a stiffly-attached load currently available. The suspension parameters of the suspended backpack developed by Rome et al. are not reported directly in their paper (Rome et al., 2006). However, the supplementary material indicates that the elastic cords of their backpack suspension stretched by approximately 50 cm to statically support a 27 kg load, indicating that the suspension stiffness is ~530 N/m. The suspension damping of this backpack is unknown, so here we assume that the suspension damping of the suspended backpack is ~100 N s/m, the approximate mean of the flexible backpack damping reported by Foissac et al.

Description	Stiffness, K_2 (N/m)	Damping, B_2 (N s/m)
Stiff suspension	$51{,}877\pm1609$	48.1 ± 9.5
Flexible suspension	5147 ± 159	10.4 ± 2.1
Stiff backpack (suspension + link)	5060 ± 978	320 ± 125
Flexible backpack (suspension + link)	3300 ± 564	96 ± 57, or ~100
Suspended backpack (Rome et al., 2006)	~530	~100