Performance assessment of the suspended-load backpack

J. Hoover · S. A. Meguid

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Abstract The suspended-load backpack is found to improve the energy efficiency of walking with a load in some scenarios. The objective of this study is to (i) analyze the dynamic load of the suspended-load backpack over a range of walking speeds and pack masses, and (ii) determine the optimal design parameters for the suspended-load backpack to minimize the effect of dynamic load on the efficiency of walking. A simple spring, damper and mass system is used to model the performance of the suspended-load backpack as well as the typical hiking pack. The oscillating load and phase angle are calculated over a range of loading and spring stiffness values to determine the system resonance and optimal spring stiffness design range for the suspended-load backpack. Our results reveal that the stiffness for the suspended-load backpack should be designed below one half of the resonance stiffness to minimize dynamic loads at a given walking speed. The location and magnitude of the maximum phase angle is also calculated. A performance comparison between the suspended-load backpack and a typical hiking pack demonstrates the beneficial range for the suspended-load backpack. The suspended-load backpack is found to provide significant reductions in the peak backpack load, compared with a typical hiking pack, while carrying large loads at fast walking speeds. The suspended-load backpack performs poorly for low pack loads due to in-phase oscillations between the pack and the walking person.

Keywords Suspended-load · Backpack · Load · Walking · Spring-model · Resonance · Stiffness · Performance · Design · Peak loads

List of symbols

- $A$: Oscillating load ratio (scaling factor)
- $c$: Equivalent pack damping coefficient
- $F_{osc}$: Oscillating pack force
- $F_{Pack}$: Total pack force
- $g$: Gravity
- $k$: Equivalent pack stiffness
- $X, Y$: Amplitude of oscillation of person and pack
- $m$: Total pack mass
- $S$: Stature (height) of person
- $t$: Time
- $v$: Walking speed
- $\omega$: Walking frequency
- $\omega_n$: Natural frequency for the pack
- $\delta$: Static deflection of pack
- $\phi$: Phase angle
- $l_0$: Leg length of person

J. Hoover (✉) · S. A. Meguid
Department of Mechanical and Industrial Engineering, University of Toronto, 5 King’s College Road, Toronto, ON M5S 3G8, Canada
e-mail: jeffery.hoover@utoronto.ca

S. A. Meguid
e-mail: meguid@mie.utoronto.ca
Vertical position, velocity, and acceleration of the torso

Vertical position, velocity, and acceleration of the pack

1 Introduction

Backpacks are commonly used to carry a wide variety of loads for hiking, military, scholastic and other pursuits. This load, coupled with the person’s height and walking speed, will lead to a loading profile from the pack acting on the person. Although user heights will vary across most pursuits, trends in loading and walking speed may be seen across particular activity groups. In military and hiking applications, for example, relatively high loads are commonly carried at high walking speeds. In the case of school-children, a variety of loads may be carried at relatively low walking speeds.

During walking, the cyclic vertical acceleration of the torso causes an oscillatory (dynamic) load in addition to the static load from the pack. This oscillatory load can be significant and of the same order of magnitude as that of the static pack load (Rome et al. 2006). Recent studies have shown the potential benefits of walking with a low-stiffness pack compared to current conventional packs by significantly reducing this oscillating load (Rome et al. 2006; Foissac et al. 2009). Rome et al. (2006) found that the oscillating force could be reduced by 86% and the metabolic cost of walking with the suspended-mass pack could be reduced below that for typical hiking packs. Others have studied the potential for energy harvesting using the suspended-mass pack; see for example, the work of Donelan et al. (2008), Niu et al. (2008), and Granstrom et al. (2007). While the current research is useful in demonstrating the potential benefits of the suspended-load backpack, the performance across a range of pack loads and walking speeds has not been examined.

The relationship between the position of a pack and its wearer can be characterized by an equivalent viscoelastic element consisting of a spring and a damper in a parallel arrangement. The equivalent element must capture both the deformation of the pack itself and the attachment between the pack and the person. Recently, Foissac et al. (2009) experimentally determined the equivalent spring and damping coefficients for the suspended-load and typical hiking pack over a range of walking speeds using this model. The equivalent stiffness pack was found to be similar to the pack stiffness for the suspended-load pack, while the equivalent stiffness for the typical hiking pack was drastically reduced below the pack stiffness. This is believed to be due to the compliance of the pack to person attachment limiting the stiffness of the system.

For the suspended-load pack, the stiffness of the pack is designed to be compliant to allow the pack contents to move up and down relative to the pack harness. Most prototype suspended-load designs include rails and bearings to allow the pack contents to move freely relative to the pack harness and springs or bungee cords to restrict the movement between the pack contents and the harness. In this manner the pack is designed to be compliant in the vertical direction while walking. The pack spring stiffness and friction can be adjusted to produce the desired equivalent stiffness values up to that of the typical hiking pack. To the writers knowledge no detailed analysis has been performed to determine the ideal parameters for the suspended-load pack to reduce the oscillating load acting on a person. Previous authors have suggested the suspended-load pack stiffness should correspond to the region of resonance for the system based on the pack load and walking speed of the individual. Others have suggested pack properties corresponding to a preferable coupling between the pack motion and walking gait (Xu et al. 2009).

The fundamental dynamic equations for oscillating load and phase shift are well established; see e.g., (Foissac et al. 2009). Existing work, however, does not include calculations for torso movement with walking speed; performance stiffness for reduced oscillating load and maximum phase shift; and scaling factor. The scaling factor gives the comparison between the suspended-load pack and the typical hiking pack. The present study makes use of the analytical equivalent viscoelastic backpack model and the experimental values of Foissac et al. (2009) to explicitly predict the oscillating load over a range of walking speeds and pack loads. The aim of this study is to (i) determine the ideal design parameters for the suspended-load pack and (ii) analyze the dynamic load of the suspended-load backpack to determine its usefulness compared with the typical hiking pack.
This analysis can be used to achieve the optimal suspended-mass backpack design for a given hiking or energy harvesting application.

2 Dynamic modelling of backpack during walking

2.1 Walking model

During the walking cycle the hips move up and down as the body is propelled forward from one leg to the other. The walking motion is characterized by a double support phase where both feet are in contact with the ground and a single support phase where one leg swings forward while the other provides support in contact with the ground. Joint movements at the hips, knees, and feet act to smooth the motion of the torso through the walking cycle. This three-dimensional complex walking motion will lead to accelerations and decelerations of the torso in the vertical, forward, and sideways directions. For the purpose of the suspended-load pack, only the torso movements in the vertical direction are of interest because the pack is designed to oscillate in this direction. Saunders et al. (1953) have shown this vertical movement of the torso can be approximated by a sinusoidal profile as per Eq. 1 below:

$$x = X \sin(\omega t)$$

(1)

The above equation describes the sinusoidal vertical profile of the torso with amplitude $X$, radial frequency $\omega$, and time $t$. As a rough approximation, the vertical displacement can be calculated using an inverted pendulum model assuming a straight leg and no hip or foot adjustments during the walking motion. In this scenario, the torso will move up as the body rotates up over the support leg and down as it rotates past the vertical support leg position before the other leg contacts the ground. A complete cycle, as given in Eq. 1, corresponds to each step where the individual’s torso will move from its lowest point (double support), to its highest point (single support with vertical contact leg), and back down to its lowest point (double support). The amplitude of oscillation of the torso is a function of the leg length $l_0$ of an individual’s height $S$ using the anthropometric data of Roebuck et al. (1975) such that,

$$l_0 = 0.535 S$$

(2)

The distance travelled during each stride will be determined by both the leg length and angles during walking. The walking speed will be a function of the step length and the walking frequency. Grieve and Gear (1966) have shown empirically that the walking frequency $\omega$ (rad/s) can be approximated from the walking speed $v$ (m/s) and height $S$ (m), viz.,

$$w = \frac{4\pi \cdot 64.8(V^{0.57})}{60}$$

(3)

Furthermore, the inverted pendulum model can be used to determine the vertical torso position while walking with a straight leg. This model can be refined further by including corrections for pelvis rotation, pelvis tilt, knee flexion, ankle position, foot length, and a narrowed walking base as shown by Xu (2008). The amplitude of oscillation of the torso, including these corrections, is given as follows,

$$X = \frac{l_0}{2} \left(1 - \sqrt{1 - \left(\frac{0.963v}{l_0 \cdot 2 \cdot 1.504(V^{0.57})}\right)^2} - 0.0157l_0\right)$$

(4)

The amplitude of oscillation is a function of the walking speed $v$ in meters per second and leg length $l_0$ in meters. Eq. 4 is shown by the theoretical line of Fig. 1 for an average individual of 1.78 m height. The torso amplitude is seen to increase with walking speed. Fig. 1 shows that Eq. 4 provides a good approximation to the experimental torso height results of Gard (2004) for an individual of 1.78 m height with no pack. The figure also shows the results of Xu (2008) for an individual of 1.77 m height and 26.7 kg total pack mass; and Foissac et al. (2009) for an individual of 1.791 m height with an 18.5 kg load and unspecified pack mass. It should be noted that Eq. 4 does not include any coupling effects between the pack and the torso—only the leg length and walking speed will influence the amplitude of oscillation in this equation.

2.2 Backpack model

The typical suspended-load backpack is shown in Fig. 2a. The pack load is isolated from the pack harness by a spring and damper. For the typical hiking pack the pack load and harness are joined, corresponding to a
high pack stiffness value. In addition to the pack deformation, the compliance of the harness attachment must be considered to accurately model the system. These two factors will define the response for the suspended-load backpack. For this study the backpack is modeled by an equivalent viscoelastic element as shown in Fig. 2b. The equivalent spring stiffness \( k \) and damping coefficient \( c \) in this model include the effects of both the harness and the pack itself as per the work of Foissac et al. (2009). The vertical position of the torso is given by \( x(t) \) and the vertical position of the load is given by \( y(t) \).

The pack load \( m \) is equal to the mass of the pack and its contents. The spring coefficient and damping are assumed to be constant, which have been found to be good approximations for the low-stiffness pack (Foissac et al. 2009). The angle of the pack from the vertical is ignored, as this angle is typically less than 8° (Kinoshita 1985), corresponding to an insignificant change in the dynamics of the system. The static deflection \( \delta \) describes the relative position between \( x \) and \( y \) (equivalent spring extension) when the system is at rest.

The sinusoidal torso oscillation of Eq. 1 applied to the backpack model in Fig. 2b will result in sinusoidal oscillations of the vertical position of the backpack (Rao 2005). The sinusoidal response of the backpack can be expressed as

\[
y = Y \sin(\omega t - \phi)
\]

where the amplitude of oscillation is given by \( Y \) and the relative phase shift of the oscillation between the backpack and person is given by \( \phi \). The characteristic equation of motion for the backpack model is given below with the spring stiffness \( k \) and damping coefficient \( c \),

\[
k(x - y) + c(\dot{x} - \dot{y}) - m\ddot{y} = 0
\]

The natural frequency \( \omega_n \) for the pack is given by the square root of the ratio of the stiffness to the mass such that,

\[
\omega_n = \sqrt{\frac{k}{m}}
\]

Solving for the steady state response of Eq. 6 gives the amplitude ratio \( \frac{Y}{X} \) and the phase shift shown in Eqs. 8 and 9 below,

\[
\frac{Y}{X} = \sqrt{\frac{k^2 + \omega^2 c^2}{(k - m\omega^2)^2 + \omega^2 c^2}}
\]

\[
\phi = a\tan\left(\frac{m\omega^2}{\omega^2 c^2 + k^2 - m\omega^2 k}\right)
\]

There will also be an additional static deflection in the spring \( \delta \) due to the gravitational acceleration \( g \) acting on the mass \( m \) such that,

\[
\delta = \frac{mg}{k}
\]
The total stretch of the spring will consist of the static deflection and the relative time varying position between the torso and the pack.

The net force of the pack acting on the person in the downward direction is equal to the sum of the force of gravity acting on the mass and the force accelerating the mass. The acceleration force is the product of the mass times the acceleration, which can be found from the second derivative of Eq. 5 with respect to time. The amplitude ratio of Eq. 8 can be used to obtain this oscillating force as a function of the torso amplitude \( X \). The resulting pack force \( F_{\text{Pack}} \) acting on the person in the downward direction can be expressed as follows,

\[
F_{\text{Pack}} = mg - |F_{\text{osc}}| \sin(\omega t - \phi)
\]  

(11)

The magnitude of the oscillating force \( |F_{\text{osc}}| \) from the pack acting on the person is given by Eq. 12. The oscillating force is a function of the walking frequency, amplitude of oscillation for the torso, pack mass, stiffness, and damping, such that,

\[
|F_{\text{osc}}| = m\omega^2 X \sqrt{\frac{k^2 + \omega^2 c^2}{(k - m\omega^2)^2 + \omega^2 c^2}}
\]  

(12)

2.3 Backpack performance parameters

The goal of the suspended-load backpack is to reduce the oscillating force and peak force acting on the person as this will ease muscle fatigue and increase energy efficiency (Rome et al. 2006). Reducing the oscillating force will improve the overall pack performance by allowing the user to walk further, carry greater loads, or exert less energy compared with using traditional packs. The oscillating load corresponding to the performance of the suspended-load pack is a function of the pack mass, walking frequency, torso amplitude, and stiffness and damping coefficients as shown in Eq. 12. For an individual walking with a given frequency, pack mass, and torso amplitude of oscillation; the goal is to determine the pack stiffness and damping coefficients to minimize this oscillating force. If the pack damping coefficient is set to zero the oscillating force can be seen to rise to infinity where the pack stiffness is equal to the mass times the walking frequency. This is the stiffness value \( k_{\text{resonance}} \) corresponding to the resonance of the system, if the damping is equal to zero; viz.,

\[
k_{\text{resonance}} = m\omega^2
\]  

(13)

Above this stiffness the oscillating force is seen to converge to a non-zero value \( |F_{\text{osc}}|_{k=\infty} \), as given below,

\[
|F_{\text{osc}}|_{k=\infty} = m\omega^2 X
\]  

(14)

Below this resonance stiffness the oscillating force can be further reduced for low stiffness values. For stiffness values near the resonance stiffness, an increase in the damping coefficient will produce a reduction in the oscillating force. For stiffness values close to zero, a decrease in the damping will produce a reduction in the oscillating force. The stiffness value, where the damping coefficient will not change the oscillating force, is defined as the performance stiffness \( k_{\text{performance}} \) in this study. Pack stiffness values below the performance stiffness will lead to the minimum oscillating load (with lower stiffness producing lower oscillating loads) and a reduction in the damping coefficient will lead to a reduction in the oscillating load for the suspended-load pack. The performance stiffness is calculated from Eq. 13 by setting the derivative of the oscillating load with respect to the damping coefficient equal to zero and solving for the spring stiffness at that location. It is then clear that the performance stiffness is a function of the pack mass and walking frequency, as follows,

\[
k_{\text{performance}} = \frac{1}{2} m\omega^2
\]  

(15)

The performance stiffness is equal to \( \frac{1}{2} \) of the resonance stiffness given in Eq. 13. The oscillating load at the performance stiffness is found by substituting the performance stiffness from Eq. 15 into Eq. 12 for the oscillating load. The resulting oscillating load at the performance stiffness is given by,

\[
|F_{\text{osc}}|_{k_{\text{performance}}} = m\omega^2 X
\]  

(16)

The stiffness corresponding to the maximum phase shift is found by taking the derivative of \( \phi \), given in Eq. 10, with respect to the stiffness \( k \) and setting the result equal to zero. The maximum phase shift \( \phi_{\text{max}} \) is found to occur at the performance stiffness as well. The maximum phase shift can now be expressed as,
\[
\phi_{\text{max}} = a \tan \left( \frac{m c \omega}{c^2 - \frac{1}{2} m^2 \omega^2} \right)
\]  

(17)

In order to determine the feasibility and overall performance of the suspended-load pack the performance of the suspended-load pack should be compared to the performance of a typical hiking pack. The scaling factor \( A \) defines this performance parameter by calculating the ratio of the oscillating load for a suspended-load pack to that for a typical hiking pack as shown by the following equation,

\[
A = \frac{|F_{\text{osc}}|_{\text{Suspended-Mass}}}{|F_{\text{osc}}|_{\text{Rigid}}} = \sqrt{\frac{k_{\text{rigid}} + c_{\text{rigid}}^2}{(k_{\text{rigid}} - m \omega^2) + c_{\text{rigid}}^2}} \sqrt{\frac{k_{\text{rigid}}^2 + c_{\text{rigid}}^2}{(k_{\text{rigid}} - m \omega^2)^2 + c_{\text{rigid}}^2}}
\]  

(18)

Since the static force is the same for two different packs carrying the same mass, only the oscillating force will be different in this comparison. For values of \( A \) below 1, the suspended-load backpack oscillating load and peak load are lower than those of the typical backpack. The goal of the suspended-load pack is to reduce the scaling factor \( A \) as much as possible. In the case where \( A \) equals zero, for example, there would be no oscillating load for the suspended-load backpack and only the static load of the pack would be felt by the user while walking. Note that the scaling factor \( A \) is not a function of the amplitude of oscillation \( X \) of the person because both packs are linearly dependent on this variable.

The relative movement of the pack and the person is an important parameter in determining the required travel for the suspended-load backpack. Excessive values for static deflection or relative displacement would reduce the feasibility for a pack design, because this travel must be accommodated by the pack and spring system. The relative movement of the pack to the person is calculated from Eqs. 1, 5, and 9 using the following expression,

\[
|x - y| = \sqrt{X^2 - 2XY \cos(\phi)} + Y^2
\]  

(19)

2.4 Backpack stiffness and damping

The stiffness and damping properties for a typical hiking backpack and a suspended-load backpack have been shown by the excellent experimental work of Foissac et al. (2009). These results are summarized in Table 1. In this study a pack was designed capable of achieving 5,000 and 50,000 N/m pack stiffness values, representing the hiking and suspended-load backpack. Using a load of 16 kg the vertical acceleration of the pack and the trunk were measured to determine the resulting total pack stiffness and damping coefficients including the effect of the pack attachment to the body. It should be noted that the total stiffness values are significantly reduced below the pack stiffness due to the harness to body attachment. The stiffness of the typical hiking backpack is found to increase with higher loads and walking speeds while the stiffness of the suspended-load backpack showed no significant dependence on pack load and walking speed. These reported values will be used to characterize the typical hiking pack and the suspended-load backpack in this study. In the case of the suspended-load backpack the damping coefficient is assumed to be constant for all suspended-load pack stiffness values.

3 Analysis of results

3.1 Practical considerations

The static deflection of a pack given by Eq. 10 is shown in Fig. 3 for a number of typical total pack mass values over a range of spring stiffness values. Reducing the spring stiffness will lead to an increase in the static deflection for a given mass. As the spring stiffness is reduced below 1,000 N/m, the static deflection can be seen to rapidly increase for a mass of 25 kg. The suspended-load pack must be designed to accommodate these large spring deflection values.

The oscillating load for a person walking with a pack is given by Eq. 12 for the equivalent spring and damper backpack model. Fig. 4 shows the oscillating load for an individual of 1.78 m height walking with a speed of 5 km/h, while carrying a total pack mass of 18.5 kg. These values were chosen to roughly relate to those of the Foissac study and to typical hiking

| Table 1 | Equivalent backpack stiffness and damping parameters (Foissac et al. 2009) |
|---------|------------------|------------------|
| Description | Stiffness (N/m) | Damping (Ns/m) |
| Typical hiking pack | 5,060 ± 978 | 320 ± 125 |
| Suspended-load pack | 3,300 ± 564 | 96 ± 57 |
parameters. At this walking speed and pack load, trunk movement is not significantly affected by the addition of the pack (Foissac et al. 2009). The vertical amplitude of oscillation is calculated to be 0.020 m, which is found to be lower than the \( \approx 0.03 \) m amplitude measured by Foissac et al. (2009). The oscillating load is calculated to be 73.4 N for the rigid pack and 132.2 N for the suspended-load pack using the stiffness and damping values of Foissac et al. (2009) given in Table 1. These values show the trend of a higher peak acceleration force for the suspended-load pack as shown by Foissac et al. (2009). The triangle in Fig. 4a shows the performance stiffness value for this walking speed and pack load. All values of damping are seen to converge at this spring stiffness for the given load and walking speed. The oscillating load in the low stiffness region is shown in Fig. 4b. The oscillating load is seen to decrease with a reduction in damping below the performance stiffness.

The phase shift as a function of the damping and spring stiffness is calculated for a typical hiking scenario using Eq. 9. These results are shown in Fig. 5. For zero damping, the pack is seen to oscillate completely out of phase with the person for low stiffness values (where the natural frequency is below the walking frequency) and completely in-phase with the person for higher stiffness values. As the damping is reduced in the low stiffness region the phase shift is increased. The performance stiffness is seen to occur at the location of peak phase shift.

3.2 Performance results

The pack performance over a range of walking speeds and pack masses is of interest to determine the overall performance of the suspended-load pack. Walking speeds will vary across individuals and pack masses can be expected to vary based on trip duration, food supply, and gear. Using Eq. 9 the oscillating load can be determined for a range of walking speeds and pack loads for the typical hiking and suspended-load pack using the stiffness and damping values of Foissac et al. (2009). These results are shown in Fig. 6. The oscillating load for the typical hiking pack (rigid pack) is shown in Fig. 6a. The oscillating load for the suspended-load pack is shown in Fig. 6b. As expected, the oscillating load increases with walking speed as the torso amplitude increases. The oscillating load for the
rigid pack increases with pack mass. The suspended-load pack shows an altered dependence on pack load, especially for high walking speeds and pack masses. The oscillating load for the suspended-mass pack designed below the performance stiffness is shown in Fig. 7. The damping coefficient is assumed to be unchanged at this lower stiffness value. The oscillating load for this pack is greatly reduced with very little dependence on pack mass above 15 kg.

The scaling factor defines the ratio of the oscillating load for the suspended-load pack to that of the typical (rigid) hiking pack. This provides a good measure of the performance of the suspended-load pack relative to the typical hiking pack. The scaling factor results are shown in Fig. 8 with values below 1 corresponding to the suspended-load pack outperforming the typical hiking pack. The performance of the suspended-load pack with the suspended-load and typical pack values of Foissac et al. (2009) is shown in Fig. 8a. The performance with the stiffness of the suspended-load pack reduced to slightly below the performance stiffness is shown in Fig. 8b. The scaling factor is seen to decrease below 1 for fast walking speeds and high pack loads in Fig. 8a and b. This shows that the suspended-load pack will produce less oscillating load than a typical hiking pack for fast walking speeds while carrying large loads. At slow walking speeds and/or low pack masses the suspended-load pack performs worse than the typical rigid pack. This is particularly the case for the suspended-load pack with higher spring stiffness shown in Fig. 8a. The lower spring stiffness pack of
Fig. 8b is seen to provide additional reduction in the oscillating load over that of Fig. 8a for all walking speeds and pack masses.

Figure 9 shows the performance lines for a suspended-load pack where the scaling factor equals 1. Lines are drawn for different stiffness values. The suspended-load pack will outperform the typical rigid pack in the upper right-hand part of the graph similar to that in Fig. 8. Figure 9 shows that the beneficial region of the suspended-load pack is reduced to lower walking speed and pack mass values as the spring stiffness is reduced. The relative oscillation between the pack and the person is shown in Fig. 10 for the low-stiffness suspended-load pack. The maximum amplitude of oscillation is seen to be 0.045 m at the maximum walking speed presented.

4 Discussion

4.1 Model assumptions and limitations

A number of assumptions were made in the analysis of the suspended-load backpack. The torso amplitude and frequency of oscillation were calculated using the inverted pendulum model with corrections for hip rotations, knee flexion, etc. These amplitudes created oscillations slightly below the experimental measurements of Gard and Foissac. The calculated values were found to be most accurate in the 3–6 km/h range (Gard 2004; Xu 2008). The oscillating load is linearly dependent on the torso amplitude so changes in the amplitude will act to increase or decrease this load. The trend of an increasing torso amplitude with walking speed is supported by the experimental results of Xu (2008) and Foissac et al. (2009) shown in Fig. 1 which suggests the trends for the oscillating load contour plots shown in Figs. 6 and 7 are correct. A change in the magnitude of the torso amplitude with walking speed will only act to stretch or compress the contour plots shown.

The interaction of the pack design (stiffness and damping) and pack mass with torso amplitude has been ignored for this study. Foissac et al. (2009) showed no significant dependence of walking speed on torso amplitude for walking speeds below 5 km/h and loads of approximately 18.5 kg (25% of body weight). The pack loads analyzed in this study correspond to roughly 25% of body weight for the average adult male. It is expected that the calculation...
of oscillating load values will be most accurate below 5 km/h. Above this walking speed the interaction of the pack and individual will reduce the amplitude of oscillation below calculated values which will reduce oscillating loads. The scaling factor demonstrating the comparison between the oscillating load for the suspended-load pack and the typical hiking pack should also be most accurate below 5 km/h as Foissac et al. (2009) showed no significant difference in torso amplitude above these speeds. At speeds above 5 km/h the greater difference in oscillating loads may produce a difference in the torso amplitude for the suspended-load pack and the typical hiking pack. This would alter the path of the trend lines shown in Figs. 8 and 9, however this effect should be less than 20% based on the experimental results of Foissac et al. (2009).

The damping and spring coefficients in the model are assumed to be constant for this analysis. This should be accurate where loads do not create excessive accelerations, velocities and deflections in the pack. Bungee cords and rubber cords are currently available that can withstand the required deflections and loads of the suspended-load backpack with low damping values. Foissac found nearly constant damping and stiffness over a range of walking speeds implying the linear assumption is a good one for the suspended-load pack. For the typical pack the pack stiffness is found to increase with walking speed with a nearly constant damping coefficient. Figure 4 shows the oscillating load for the rigid pack will not change significantly with an increase in spring stiffness because the curve flattens out at high stiffness values. As a result, the spring and damper model shown should accurately describe the system.

4.2 Design parameters

A number of important features of the suspended-load pack have been drawn from the current study. Our results show that the suspended-load pack is seen to provide a significant reduction in the oscillating load for low-stiffness and damping values. By reducing the pack stiffness below the performance stiffness the resonance effects during walking can be avoided. The stiffness of the suspended-load pack should be designed in this range to minimize the dynamic loading on the user. The damping in the suspended-load pack was shown by Foissac et al. (2009) to be less than that of a rigid pack so the effects of resonance can cause significant increases in the oscillating load for the suspended-load backpack. In the region below the performance stiffness a reduction in damping is shown to reduce the oscillating load further. The suspended-load pack is capable of producing significant reductions in the oscillating load by optimizing these design parameters. A suspended-load pack with a spring constant of 1,000 N/m and a damping coefficient of 100 Ns/m can reduce the oscillating load by as much as 80% under typical hiking scenarios based on the calculations of this study.

Another interesting property of the performance stiffness is the fact that the phase shift is maximized at this point. It has been suggested that the phase shift of the oscillating load may impact the overall energy efficiency during walking by locating the peak load toward the most efficient region of the walking stride (Xu et al. 2009). Figure 5 shows a maximum phase shift of 95.7° for the suspended-load pack with a pack load of 18.5 kg, 100 Ns/m damping coefficient, 1.78 m height, and 5 km/h walking speed. This would shift the peak load to the efficient single support phase of the walking cycle. Reducing the stiffness below the performance stiffness will maintain most of these phase shift benefits as well. Further analysis of the energy efficiency while walking with different pack-to-person phase shift values for a given loading could allow for the suspended-load backpack to be optimized within this region.
4.3 Overall performance

The suspended-load pack is found to be most useful while walking at fast walking speeds carrying large loads. When carrying low pack mass, the suspended-load backpack is seen to perform worse than typical packs as shown in Fig. 8. As a result, the suspended-load backpack may be best suited to military and hiking applications where large loads are typically carried at relatively high walking speeds. In scholastic applications, loads vary drastically based on whether textbooks and other belongings are carried. Walking speeds and heights would be smaller as well, thus limiting the improvement with the suspended-load pack. With this in mind, the suspended-load pack can produce significant improvements when used in the correct application.

5 Conclusions

The benefits of the suspended-load pack are maximized by reducing the pack stiffness and damping to as close to zero as possible. The reduction of the spring coefficient is limited by the static deflection that the pack and springs can accommodate. The suspended-load pack is most useful while walking at fast speeds with large pack loads. In this region the suspended-load pack can reduce oscillating loads by as much as 80%. Reducing the spring stiffness for the suspended-load pack will increase the useful range for the pack. For low pack masses and walking speeds the suspended-load pack is outperformed by typical hiking packs. The relative pack-person oscillation amplitude is less than 5 cm for the low-spring stiffness suspended-load pack. This corresponds to an achievable value for a pack design.

Walking with a frequency that matches the resonance frequency for the pack load and stiffness will lead to high-oscillating loads for the user. The suspended-load pack should be designed with a reduced stiffness value below the performance stiffness for a given pack load and walking frequency. This will minimize the oscillating load and fatigue during walking with the suspended-load pack.

References