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An Empirical Validation of a Base-excitation Model to Predict Harvestable Energy From a Suspended-load Backpack System

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Abstract

Suspended-load backpacks have been proposed as a way to provide power for small electronic devices by capturing the mechanical energy generated by the vertical movement of the suspended load and converting it into electrical energy. The aim of the current study was to build a base excitation model able to predict the relative velocity of the load (an index of the amount of harvestable energy of such a system) using as inputs the mass of the suspended load, the walking speed and the leg length of the user. Nine human participants walked on a treadmill under two load conditions (15.8 kg and 22.6 kg load) and three walking speed conditions (1.16 m/s, 1.43 m/s and 1.70 m/s). The predictions of the load velocity by the base-excitation model under these conditions were then compared with the measured load velocity. The results of this study showed a moderately strong correlation (0.76) between the RMS of the predicted and measured relative velocity of the load and the average absolute error of these predictions was 24.2%. These results provide support for the utility of this approach and also provide motivation for further refinement of the base excitation model for the prediction of the amount of energy able to be harvested from suspended load backpack systems.

Keywords: Suspended-load backpack, load carriage, walking speed

1. Introduction

The increasing ubiquity of electronic mobile devices (cell phones, PDAs, mp3 players, GPSs, etc.) combined with limitations in battery longevity, have led many to search for ways to harvest energy from everyday activities to power these, and other, devices. Approaches to harvesting this mechanical energy have included piezoelectric pads to convert pressure into energy, exoskeleton devices to convert angular motions into energy and backpack mounted systems that convert the vertical motions of a backpack load during gait into energy, to name just a few. Of particular interest in the current study is a backpack system developed by Rome and colleagues (Rome et al., 2005). In this system a load is suspended by springs within the framework of a rigid backpack frame and moves parallel to the vertical supports of the backpack. Attached to this suspended load is a toothed rack that interacts with a pinion gear that is firmly affixed to the rigid backpack frame. A generator converts this motion into electrical energy as the load oscillates with varying velocity relative to the backpack frame. Faraday's law tells us that the induced electromagnetic force is proportional to the time rate of change of the magnetic flux through the circuit. In empirical testing of the Rome et al. (Rome et al., 2005) backpack system, a 38 kg suspended load had a range of motion of 4.5 cm and the linear velocity of the rack drove the dc motor generator up to 5000 rpm. This particular example generated an average electrical power of 5.6W. In other combinations of walking speed and load mass, these authors were able to show a maximum electrical power of 7.37 W.

A system of this sort can be modeled in a fairly straightforward manner using a base excitation model, but is, however, complicated by the human performance aspects of gait (inter-step variability, axial rotation of the torso, departures from a perfectly sinusoidal vertical displacement of the trunk center of mass, etc.) The focus of the current work was the development and empirical validation of a base excitation model of this suspended load backpack system. If successful, this model would provide a method for predicting energy production of such a system as a function of backpack load mass and walking speed. In this paper we begin with the development of a model of the movement of the trunk (and thereby the backpack frame) and then develop the base excitation model of the suspended load. These models are then evaluated empirically by comparing the predicted relative velocity of the load with the measured relative velocity of the load, under different load mass and walking speed conditions.

2. Modeling

2.1 Trunk movement modeling

At its most basic level, the movement of the center of mass (CoM) of the torso during walking can be approximated by a simple harmonic vibration with a total displacement of 3 to 5 cm (Inman, 1966, Saunders et al., 1953, Smith et al., 2002). In an attempt to model this cyclic vertical motion of the center of mass of the torso, Saunders et al. (Saunders et al., 1953) proposed a simple inverted pendulum model (or "compass model") of human gait (Figure 1) and then immediately identified six "primary determinants" - factors that would modify the simple arc motions of the center of mass of torso that would be predicted from a simple inverted pendulum model. While there has been some discussion of the validity of these six determinants (Gard and Childress, 2001, Kerrigan et al., 2000)， more recent research (Della Croce et al., 2001) noted that these determinants were “generally correct”. The first five of these determinants addressed modification of vertical motion and are considered in the current work. We begin with the basic inverted pendulum model and then add the modifications as defined by the determinants.

Insert Figure 1 About Here

In the basic model, step length can be expressed as

$$L_{step} = 2l_0 \sin\theta \tag{1}$$

where l_0 is the leg length, θ is the half of the angle between two legs during the double support phase of the gait cycle, and L_{step} is the step length. Expressing step frequency ω_b in terms of the proportion of the gait cycle achieved per unit time (rad/sec), walking speed (*V*) is the step frequency times step length:

$$V = \frac{\omega_b}{2\pi} \cdot L_{step} \tag{2}$$

The magnitude of the vertical displacement of center of mass of the torso (*D*) from its highest position at mid stance to its lowest point at double support is

$$D = l_0(1 - \cos\theta) \tag{3}$$

Substituting Equations (1) and (2) into (3) yields Equation (4). Equation (4) expresses the displacement of the CoM as a multivariate function of walking cadence, leg length, and walking speed:

$$D = l_0\left(1 - \sqrt{1 - \left(\frac{\pi V}{l_0 \omega_b}\right)^2}\right) \tag{4}$$

Since none of determinants identified by the Saunders et al. (Saunders et al., 1953) have yet been considered, this is a simplified estimate of the vertical displacement of trunk from its highest position (mid stance) to its lowest position (dual stance).

The 1st determinant proposed by Saunders et al. (Saunders et al., 1953) was that the pelvis twists about the vertical axis during the gait cycle (Figure 2). The average maximum twist is about 5° with normal walking (Murray et al., 1964). From anthropometric data, the mean distance between hip joints is about 33cm (Roebuck et al., 1975). With a mean step length of 77.5cm (Whittle, 1996), the percentage of the step length that is contributed by transverse rotation of pelvis (L_p) can be calculated

$$L_p = \frac{33cm \cdot \sin(5^\circ)}{77.5cm} = 3.7\% \tag{5}$$

This ratio is suitable in terms of most walking speed because the pelvic rotation is approximately proportional to the step length (Lamoreux, 1971). Therefore, the leg swing accounts for 96.3% of the step length during normal walking and this will affect the displacement of the time-dependent CoM by elevating the ends of the arc of its motion. Equation (1) becomes

$$0.963 \times L_{step} = 2l_0 \sin\theta \tag{6}$$

Insert Figure 2 About Here

The 2nd determinant was that the pelvis is oblique downwards to the side of the swing leg in the coronal plane at mid stance (Figure 3). The angle of this collateral drop is about 7° (Perry, 1992). According to the anthropometry data (Clauser et al., 1969), the ratio of hip breath to leg length is estimated at 0.26. Thus, the reduction of the vertical position of the CoM of the torso at its highest (mid stance) point due to pelvic tilt (D_{tilt}) is

$$D_{tilt} = \frac{0.26 l_0}{2} \times \sin 7^\circ = 0.01584 l_0 \qquad (7)$$

Insert Figure 3 About Here

The 3rd determinant was that the support knee flexes during mid-stance (Figure 4) thereby reducing the height of the CoM of the torso. The knee angle is about 12° when the hip joint reaches the apex (Whittle, 1996) and the height of knee joint is 53.8% of the height of hip joint during upright standing (Roebuck et al., 1975). Based on the law of cosines, the reduced height of the CoM of the torso at its highest (mid stance) point due to knee flexion (D_{knee}) can be expressed as:

$$\begin{aligned} D_{knee} &= l_0 - \sqrt{(0.538 l_0)^2 + (0.462 l_0)^2 + 2 \times 0.538 l_0 \times 0.462 l_0 \times \cos(12^\circ)} \\ &= 0.00545 l_0 \end{aligned} \qquad (8)$$

Insert Figure 4 About Here

The 4th and the 5th determinants describe the influence of the ankle joint at heel strike and toe-off, respectively. At heel strike the ankle joint is superior to the heel due to the dorsi-flexion of the foot. At toe off, the ankle joint is elevated from the ground through the plantar flexion of the foot. Both of these tend to raise the CoM of the torso at its lowest (dual stance) point (Figure 5). Considering the foot length is 28.7% of the leg length (Roebuck et al., 1975), the increase in vertical position of the CoM at dual stance is

$$D_{ankle} = \sqrt{l_0^{\,2} + \left(\frac{0.287 l_0}{2}\right)^2} - l_0 \qquad (9)$$
$$= 0.01024 l_0$$

Therefore, by combining all the modifications to the vertical range of motion of the CoM of the torso as defined by these five determinants Equation (4) becomes

$$D = l_0\left(1 - \sqrt{1 - \left(\frac{0.963\pi V}{l_0 \omega_b}\right)^2}\right) - 0.01584 l_0 - 0.00545 l_0 - 0.01024 l_0$$
$$= l_0\left(1 - \sqrt{1 - \left(\frac{0.963\pi V}{l_0 \omega_b}\right)^2}\right) - 0.03153 l_0 \qquad (10)$$

Insert Figure 5 About Here

The amplitude of the harmonic vibration (Y) is half of the displacement of CoM:

$$Y = \frac{l_0}{2}\left(1 - \sqrt{1 - \left(\frac{0.963\pi V}{l_0 \omega_b}\right)^2}\right) - 0.01577 l_0 \qquad (11)$$

and this describes the amplitude of the approximated sinusoidal motion of the CoM of the torso and thereby the frame of the backpack. Finally, because the trunk may lean forward while carrying a backpack and only the relative movement of the suspended load along the long axis of the backpack frame is captured as an energy source, only a component of the vertical motion of the CoM of the torso is along the long axis of the backpack frame:

$Y \cos\alpha$, where α is the flexion angle of the trunk. The time-dependent motion of backpack frame along the long axis of the frame, $y_f(t)$, can be expressed as:

$$y_f(t) = Y \cos\alpha \sin\omega_b t \tag{12}$$

By differentiating Equation (12), the velocity of the base along the direction of the frame is:

$$\dot{y}_f(t) = \omega_b Y \cos\alpha \cos\omega_b t \tag{13}$$

2.2 Suspended-load modeling

Modeling the suspended-load within this backpack frame is based on a base excitation model. The suspended-load backpack can be simplified to a second-order mass-spring-damper system with mass m, spring stiffness k, and damping coefficient c. With the forward flexion of the trunk, the equivalent spring stiffness is amplified to

$k' = (k / \cos\alpha)$. (14)

According to a base excitation model (Inman, 2001), the time-dependent movement of the suspended load along the frame, $x_f(t)$, can be expressed as:

$$x_f(t) = \omega_n Y \cos\alpha \sqrt{\frac{\omega_n^2 + (2\zeta\omega_b)^2}{(\omega_n^2 - \omega_b^2)^2 + (2\zeta\omega_n\omega_b)^2}} \cos(\omega_b t - (\theta_1 + \theta_2)) \tag{15}$$

Where $\omega_n = \sqrt{\frac{k'}{m}}$, $\zeta = \frac{c}{2\sqrt{k'm}}$, $\theta_1 = \tan^{-1}\frac{2\zeta\omega_n\omega_b}{\omega_n^2 - \omega_b^2}$, and $\theta_2 = \tan^{-1}\frac{\omega_n}{2\zeta\omega_b}$.

By differentiating Equation (15), the velocity of the payload along the backpack frame is

$$\dot{x}_f(t) = -\omega_n\omega_b Y \cos\alpha \sqrt{\frac{\omega_n^2 + (2\zeta\omega_b)^2}{(\omega_n^2 - \omega_b^2)^2 + (2\zeta\omega_n\omega_b)^2}} \sin(\omega_b t - \theta_1 - \theta_2) \tag{16}$$

and the relative velocity between the payload and the frame *v(t)* can be written as:

$$v(t) = -\omega_n \omega_b Y \cos\alpha \sqrt{\frac{\omega_n^2 + (2\zeta\omega_b)^2}{(\omega_n^2 - \omega_b^2)^2 + (2\zeta\omega_n\omega_b)^2}} \sin(\omega_b t - \theta_1 - \theta_2) - \omega_b Y \cos\alpha \cos\omega_b t \qquad (17)$$

Since this relative velocity is sinusoidal, the RMS (root-mean-square) value is used to represent the average:

$$V_{rms} = \frac{1}{\sqrt{2}} \sqrt{\dot{X}_f^2 + \dot{Y}_f^2 - 2\dot{X}_f \dot{Y}_f \cos\left(\theta_1 + \theta_2 - \frac{\pi}{2}\right)} \qquad (18)$$

where $\dot{X}_f$ and $\dot{Y}_f$ are the amplitude of $\dot{x}_f$ and $\dot{y}_f$. Equation (18) demonstrates that the relative velocity between the load and the backpack frame, is a multivariate function defined by two sets of variables. The first set consists of anthropometric data and gait parameters including leg length (l_0), walking speed (*V*), and cadence (ω_b). The second set consists of the mechanical parameters of the backpack including the load mass (*m*), the spring stiffness (*k*), and the damping coefficient (*c*). The bridge between the two variable sets is the movement of the trunk which is determined by the human performance and plays a role as the excitation source of the backpack (Figure 6).

Insert Figure 6 About Here

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3. Experimental Methods

3.1 Participants

To assess the quality of the predictions of this proposed model, an experiment was conducted. Nine male subjects were recruited from the North Carolina State University student body and volunteered to participate. None of the participants had previous experience with suspended-load backpacks. The subject group had a mean age of 26.3 (SD 1.5) years, height 177 (SD 4.2) cm, leg length 95 (SD 1.9) cm, and body mass 70.8 (SD 12.0) kg. The experimental protocol was approved by the Institutional Review Board for the Protection of Human Subjects in Research.

3.2 Apparatus

Backpacks for carrying heavy loads often have a stiff frame with hip belts which transfer a portion of the load from the shoulders to the hips (Knapik et al.,1996) and improve walking stability (Sharpe et al., 2007). Previous research (Kirk and Schneider, 1992) showed that the difference between external and internal stiff frame backpacks was not significant in terms of metabolic and perceptual variables. Since an external frame backpack is convenient for refitting to become a suspended-load backpack system, a military ALICE external frame backpack was chosen in the current research. A suspended aluminum plate was added between the original external frame and the sack (Figure 7). The whole backpack system was secured to the torso through the shoulder straps and a hip belt. The load was suspended by four springs and was free to move up and down through four Teflon bushings. The equivalent spring stiffness was about 4000 N/m, while the equivalent damping coefficient was about 0.7. The dimension of the frame was length by width by height of 66 cm by 32 cm by 9 cm and the mass was 6.7 kg. Two motion sensors from a magnetic field-based motion tracking system (Ascension Technology Corporation VT, USA) were used to capture the time dependent velocity of the suspended load relative to the backpack frame. One motion sensor was fixed to the sternum of the subjects to measure the range of motion of the trunk movement. These data were collected at a rate of 60 Hz. The walking speed was controlled by Gaitway Instrumented Treadmill (Model 685, Kistler Instrument Corp.).

Insert Figure 7 About Here

3.3 Experimental Design

In this study, there were two independent variables: mass of the suspended load and walking speed. The two levels of suspended load mass were 15.8 kg and 22.6 kg load and the three levels of walking speed were 1.16 m/s, 1.43 m/s and 1.70 m/s.

The dependent variable of interest in this study is related to the energy production capability of the suspended load backpack system. Since the amount of electrical energy produced by a given system is governed by the particular generator that is employed to harvest this energy, we chose to use a more generalizable index of energy production – the relative velocity of motion of the suspended load. In this study, the specific measure considered was the RMS of the relative velocity of the suspended load (relative to the backpack frame.)

3.4 Experimental Procedures

To begin the experimental session, the suspended-load backpack was placed on the back of the subject and the shoulder belts and hip belt were securely fastened to eliminate the movement between the torso and the backpack frame. One motion tracking sensor was mounted on the backpack frame and one sensor was mounted on the plate supporting the suspended load. During the experiment, the subjects walked on the treadmill with their preferred cadence under each of the six combinations of load mass and walking speed. Each condition was performed for 1.5 minutes and the last 60 seconds were monitored by the motion tracking system. Experimental trials were conducted in a completely randomized order and a five- minute break between trials was provided.

3.5 Data Analysis

A total of 54 trials (9 subjects × 6 walking conditions) were available for analyzing the accuracy of the model. The values for the estimated $\hat{V}_{rms}$ were simply calculated for each of these 54 trials using Equation (18). The values for the measured V_{rms} were found by calculating the difference between the velocity of suspended load and the velocity of the backpack frame at each point in time (both, of course, along the direction of the frame) and then taking the RMS of this series of data points. The correlation coefficient between the predicted and measured RMS values was found and the absolute error was calculated for each of the 54 observations:

$$E = \left| \frac{V_{rms} - \hat{V}_{rms}}{V_{rms}} \right| \tag{19}$$

ANOVA procedures were used to evaluate the effects of load mass and walking speed on the RMS of the measured relative velocity data (V_{rms}). A p-value of <0.05 was considered significant in this analysis.

3. Results

The correlation between the predicted and measured range of motion of trunk movement was 0.78, and the correlation between the predicted and measured RMS of the relative velocity was 0.76 indicating a moderately strong relationship. The absolute error on predicted RMS of the relative velocity averaged across all 54 data points was is 24.2% (Figure 8.) The results of the ANOVA procedure showed that both load mass (p=0.0022) and the walking speed ($p<0.0001$) had a significant effect on V_{rms}, while their interaction did not (Figure 9).

Insert Figures 8 and 9 About Here

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4. Discussion

In terms of the proposed mechanical model, the results of this study showed a good agreement between the value of V_{rms} predicted by the model and the value found in the experiment. In terms of the relationship between this measure of relative velocity and the task variables (load mass and walking speed), increases in these task variables led to significant increases in the resulting relative velocity. This result agrees with the previous research of Rome et al.(Rome et al., 2005). However, caution must be taken when considering an extrapolation of these results. According to the base excitation model, the excited magnitude increases as the base frequency increases from zero to the natural frequency of the system. After the base frequency exceeds the natural frequency, the excited magnitude decreases. In the current study, since the changes in the suspended load mass leads to changes in the natural frequency of the backpack system, the relationship between V_{rms} and walking speed and/or load mass may be not monotonic. To clarify this question, a simplification of the model will be helpful. In Equation (11), walking speed V and cadence ω_b are two variables that influence the amplitude of the oscillation. Grieve and Gear (Grieve and Gear, 1966) proposed that there was an exponential relationship between step frequency and relative walking speed:

$$f = 2 \times 64.8\left(\frac{V}{S}\right)^{0.57} \text{ (min}^{-1}\text{)} \tag{20}$$

where f is step frequency, and S is stature. Converting the units of this result from steps/minute to radians/sec (multiply by 2π and divide by 60) and then converting stature into leg length (leg length = 0.53* S (Roebuck et al., 1975)), Equation (11) can be rewritten as

$$Y = \frac{l_0}{2}\left(1 - \sqrt{1 - \left(\frac{0.963V}{3.008 l_0 \times \left(\frac{V}{l_0}\right)^{0.57}}\right)^2}\right) - 0.01577 l_0 \tag{21}$$

For a specific suspended-load backpack condition, leg length, spring coefficient and damping coefficient are fixed. Thus, after combining Equations (18), (20) and (21), the V_{rms} can be written as a function of load mass and walking speed:

$$V_{rms} = f_{k,c,l_0}(m, V) \tag{22}$$

Since Equation (22) is a two-variable function, the relationship between V_{rms} and walking speed / load mass can be graphically represented. Figure 10 indicates that Equation (22) is not monotonic with a small damping coefficient. However, this does not contradict the experimental results of the current study because the shape of this function becomes monotonic when the damping coefficient increases to the value used in the current experiment (Figure 11). Further experimentation with a suspended load backpack system with a lower damping coefficient could provide a better understanding of the generalizability of the current model to these different systems.

Insert Figures 10 and 11 About Here

There are some limitations to the generalizability of the results of the current research that need to be discussed. First, the model was developed based on previous research that utilized the average values of certain anthropometric dimensions in their formulations (e.g. Equations 5 and 7). Refining these models to an individual's anthropometry may result in more accuracy of the model's predictions. Second, the suspended-load backpack used in the experiment was modeled as a pure time-invariant second order system which oversimplifies the realities of the physical system. The spring stiffness and damping coefficient tend to change during the load oscillating because of the swing of the torso and the abrasion of the Teflon bushing. Third, the locus of CoM of torso during walking does not follow a perfect sinusoidal curve and deviations from the perfect sinusoidal curve also contribute to the movement of the backpack. The current model does not consider these components. These limitations indicate that, while the model does an adequate job of predicting the motion of the suspended load, further refinements and improvements are possible.

5. Conclusions

Suspended load backpacks represent an interesting way to convert mechanical energy into electrical energy for use in small electronic devices. A base excitation model was developed to predict the relative velocity of the suspended load which can serve as a measure of the energy-producing capacity of the system. In this study, these predictions were compared with the empirical data describing these motions. For the conditions explored in this study, the results have shown this model to provide good predictions of the relative velocity of the load under a set of reasonable backpack conditions. Further empirical research is needed to validate the model over a wider variety of conditions.

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LIST OF FIGURES

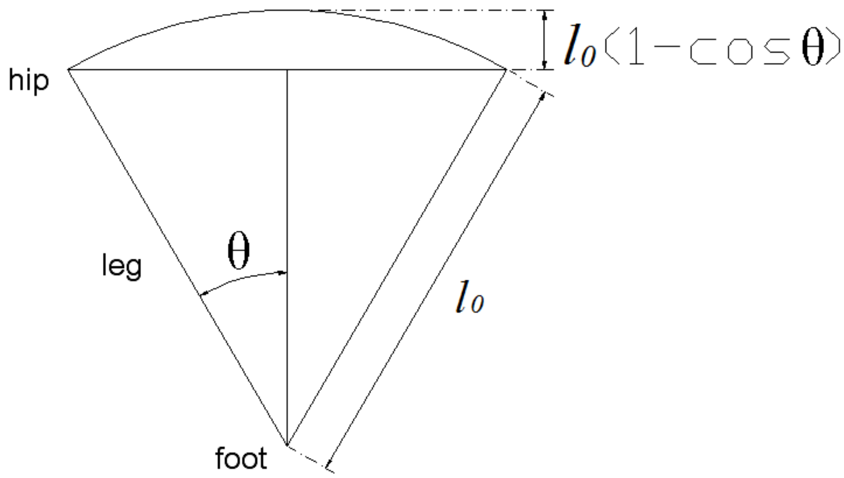

Figure 1. The inverted pendulum model for walking.

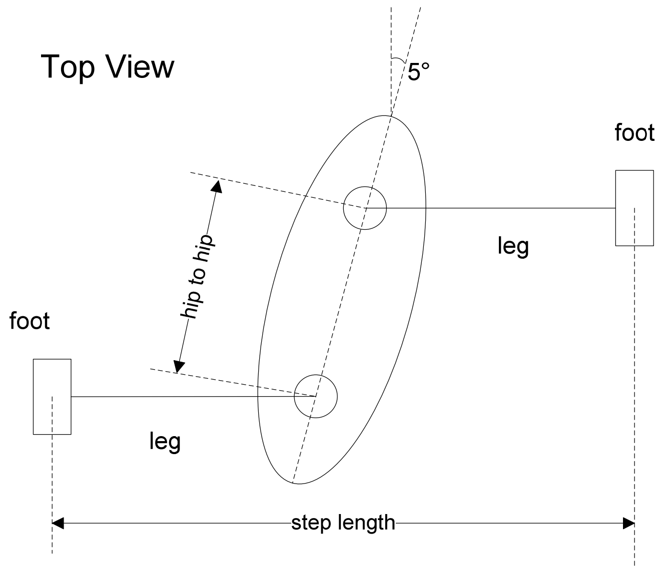

Figure 2. The pelvis twist during human walking.

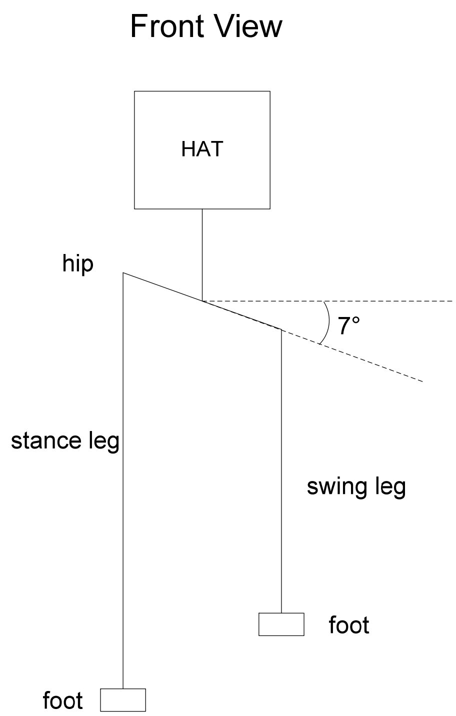

Figure 3. The pelvis obliqueness in the coronal plane during human walking. HAT stands for head, arm, and trunk.

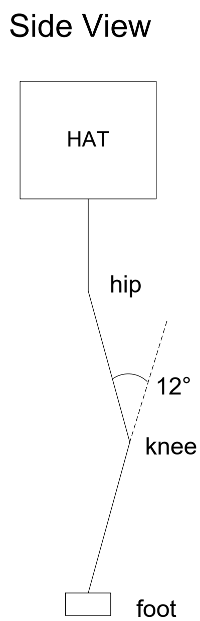

Figure 4. The knee mechanism during human walking.

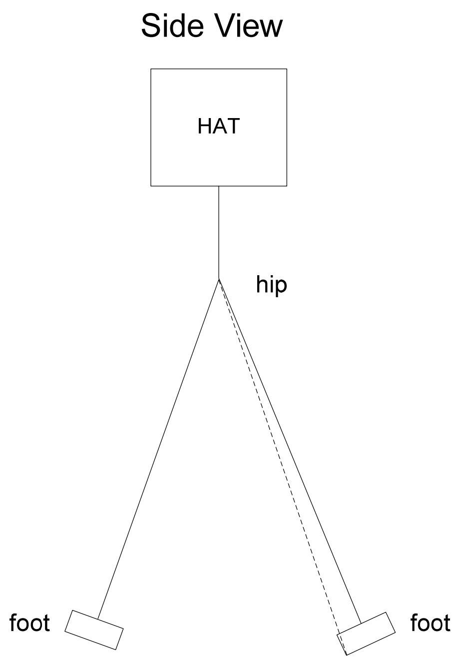

Figure 5. The foot mechanism during human walking.

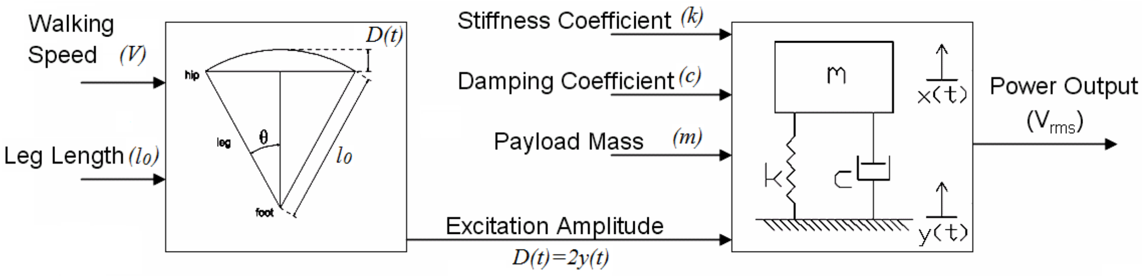

Figure 6. The diagram of the model.

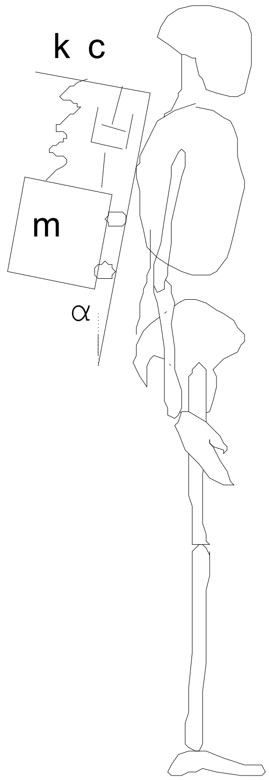

Figure 7. The configuration of the suspended-load backpack. k=spring stiffness; c=damping coefficient; m=mass.

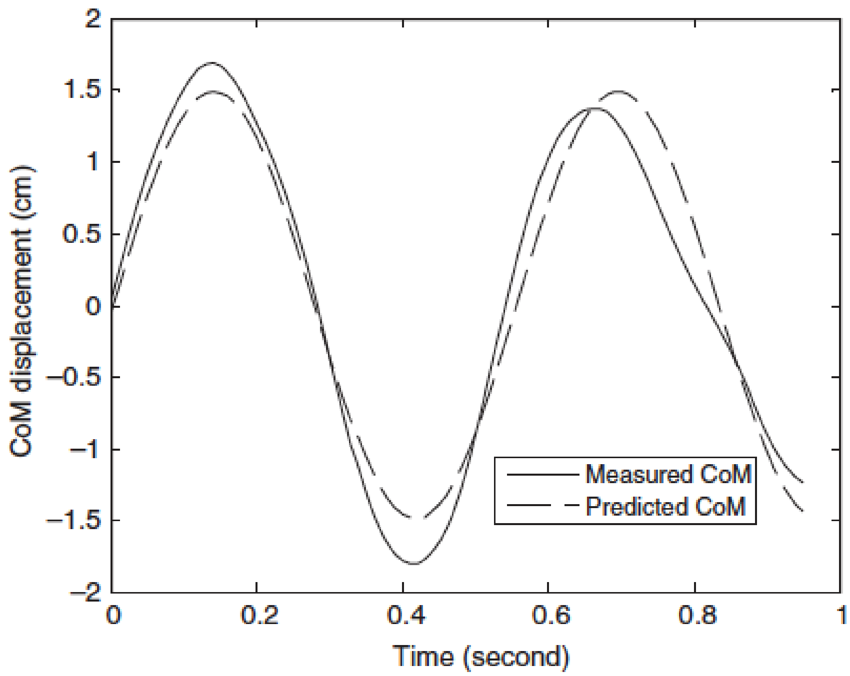

Figure 8. An example of measured and predicted movement of centre of mass (CoM) during walking (walking speed=1.16 m/s).

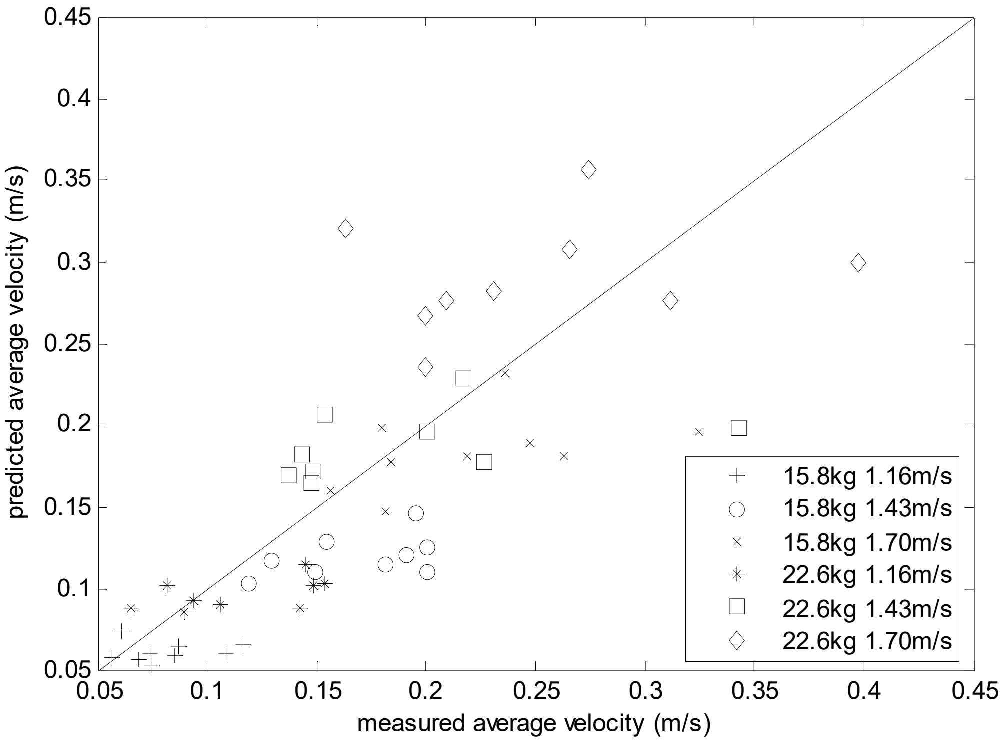

Figure 9. The scatter plot for the measured vs. predicted RMS of the relative velocity of the suspended load.

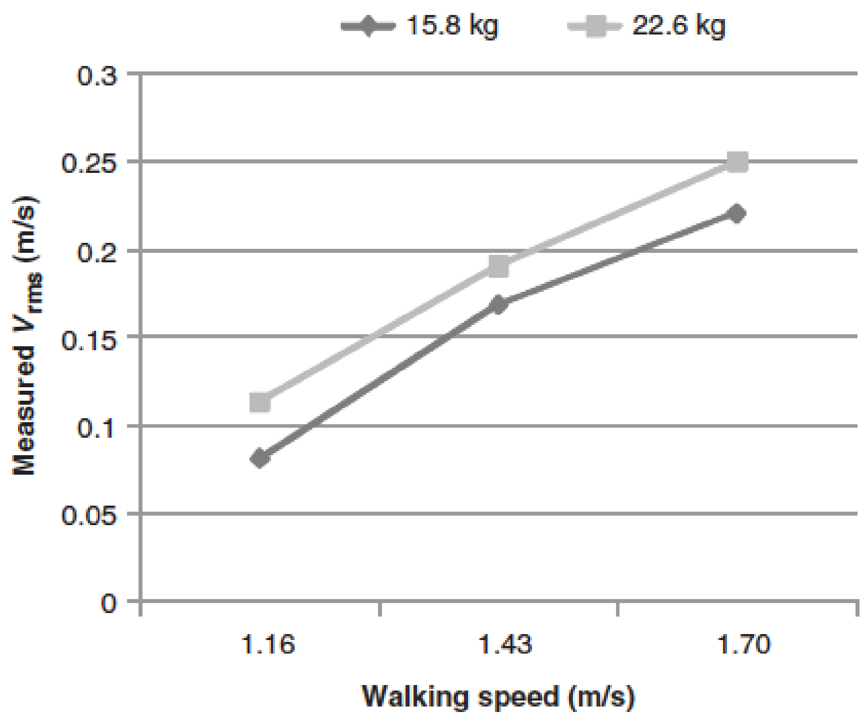

Figure 10. The effect of walking speed and load mass on the measured root mean square of the relative velocity of the load to the back pack frame. Vrms is the root mean square of relative velocity between payload and the frame.

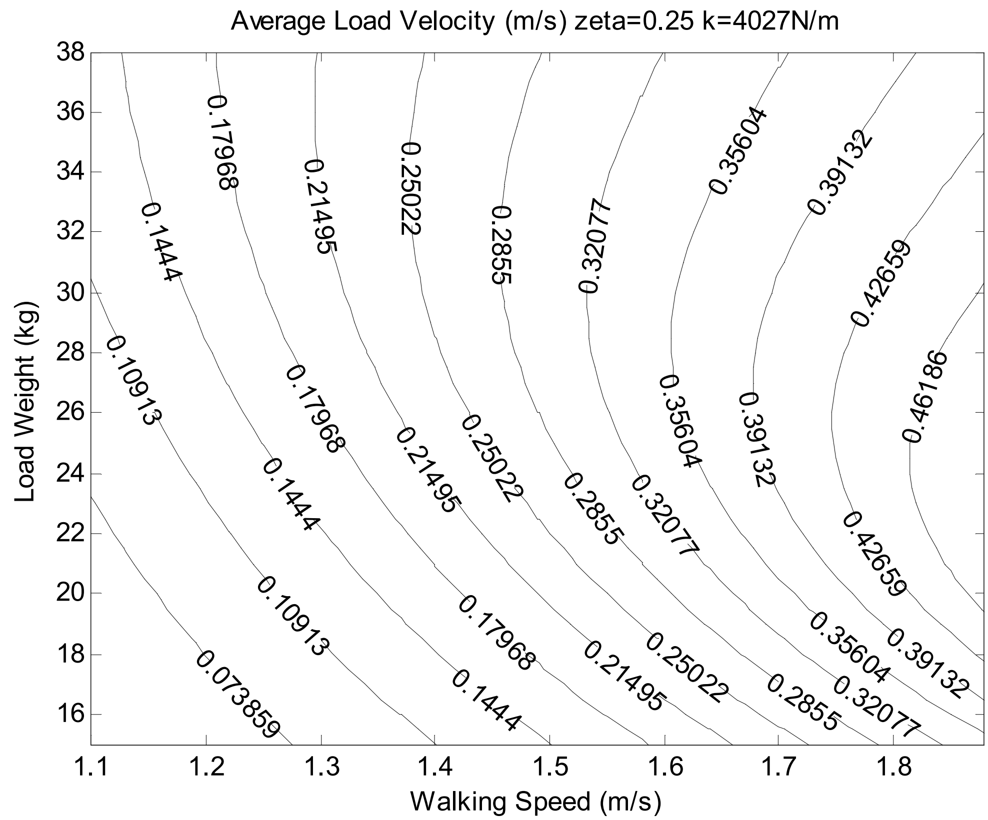

Figure 11. The predicted V_{rms} of the suspended load for different walking speed and load mass with a small damping coefficient.