Frequency Damping Backpack Exoskeleton with Load Variable Spring Stiffness

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Abstract. Heavy backpacks are one of the major reasons for spinal, neck and shoulder related problems. It also affects the human posture in an adverse way. This a major concern among school children, who have to carry heavy textbooks and stationery material. The suspended load backpack is designed to tackle these problems. However the major flaw in these backpacks is the fixed spring constant despite a range of various loads being acted upon it. Furthermore, the current frame is heavy and uses a complex damping technique. In this paper, we make a mechanism to vary the spring stiffness of the backpack according to its payload without having to adjust the damping coefficient. The redesigning of the straps ensures even load distribution during running, jumping, etc. We use a power screw type mechanism coupled with a spring to add preload. We also simulate the model to validate and differentiate between the performances.

1. Introduction
The Floating Backpack eliminates the accelerative forces that cause injuries and reduce mobility. The heavy backpacks kids are made to carry deteriorate their posture. Also, is known to give them chronic problems. Spine is made of 33 bones called vertebrae. Between the 33 bones of the spine i.e. the vertebrae, there exist disks that impose as natural shock absorbers. Improper posture while carrying heavy loads can cause various complications. Due to the heavy weight, they get pulled backwards. To make up for this unbalanced force, they may bend forward at the hips or arch their back. This compensation for improper distribution causes the shoulders and the upper back to become curved unnaturally. All of these factors contribute towards discomfort or an injury toward the neck and backside of the. Kyphosis, the slouching of the back, puts additional strain on our muscles. Ignoring physical withdrawals like soreness and discomfort in the back, can lead to persistent health issues [1]. Erroneous posture puts a lot of stress on the muscles which subsequently makes the body work harder to maintain a vertical posture instigating the person to feel exhausted. When the body is in an abnormal position, it incessantly tries to work back to where it’s supposed to be. This constant work that the body puts in to correct the posture consumes energy which instigates the feeling of fatigue.

Using a simple suspension mechanism, we are reducing the impact felt by the back area, reducing the load that the kid feels. Just like in a trophy truck, there’s a vertical movement of the wheel, whilst the truck body remains unfazed by its motion. The bag entails a similar mechanism, wherein, the frame is attached to the body and the suspension links are attached to the backpack. The spring compensate for
the vertical motion of the body. For adjusting the spring damper, there is a worm gear drive which changes the spring stiffness as the bag is being loaded for optimal spring damping of the load. The major application of this design is in the Armed Forces, where heavy loads have to be carried out in extreme terrains, and stability is a major issue.

2. Equation Modelling

2.1. Body Modelling

While designing the suspended-load pack, the vertical direction of body motion is considered because the pack is meant to oscillate along this direction. The motion of the body centre is often approximated by a sinusoidal profile as per (1) given below [2].

\[ x = X \sin(\omega t) \]  

(1)

Where \( X \) is the amplitude, \( \omega \) is the radial frequency, and \( t \) is the time. Using this approach, the vertical movement can be validated using an inverted pendulum model with the straight leg acting as the oscillating body. This relates to the concept of the pendulum, where the upper body will oscillate once about the support leg before the other leg contacts the ground. A variant of this popular algorithm, as given in (1), resembles each step where the person’s body will move from the lower trough on both the legs, to its upper crest on a single leg returns back to its initial lower trough. The design of the current study can be used to determine position of the body with the straight leg model. The key parameters, including the amplitude of oscillation may be summarised as follows

\[ X = \frac{l_y}{2} \times 1 - \vartheta \]  

(2)

, wherein \( l_y \) and \( v \) denoting the length of the leg the trodding velocity. The leg length for an average Indian is approximated to be using the available anthropometric data [3].

2.2. Frame Motion

The main schematics of our backpack consist of three springs and two dampers. The frame associated with the body is connected to the backpack using spring and dampers [4]. Introduction of sinusoidal equation in the backpack trajectory undertakes a motion similar to that of the body. This was expressed as the following formula,

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

(3)

Similar to (1), the \( Y \) represents the amplitude of the body and \( \phi \) denotes the relative phase shift of the backpack with respect to the body motion [5]. The application of the spring stiffness \( k \) and damping coefficient \( c \) in the typical equation of motion for the backpack model is demonstrated below

\[ k(x - y) + \frac{c}{2}(\dot{x} - \dot{y}) - m\ddot{y} = 0 \]  

(4)

\[ c = \frac{k_1 k_2}{k_1 + k_2} \]  

(5)

Equation (4), when solved for a steady state response, provides the amplitude ratio in (6) and the phase shift in (7) as represented below,

\[ \frac{|y|}{X} = \left( \frac{k^2 + \omega^2 c^2}{(k - m\omega^2)\omega^2 c^2 + k^2} \right)^{\frac{1}{2}} \]  

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

(6)

(7)

In addition, a static deflection in the spring will be observed due to the weight the empty backpack and load inside it, such that

\[ \delta = \frac{mg}{k} \]  

(8)

It should be noted that the total elongation of the spring will comprise of the static deflection due to load and the relative phase shift in the positions of the body and the bag. The total force exerted by the backpack in the downward direction is equal to the sum of the weight acting on the frame and the force experienced by the backpack due to the motion. The following equation expresses the resulting frame force \( F_{\text{frame}} \) experienced by the body in the downward direction.
\[ F_{\text{frame}} = mg - |F_{\text{osc}}| \sin(\omega t - \phi) \]  

(9)

In the equation derived above, the amount of the oscillating force \( |F_{\text{osc}}| \) from the frame acting on the person can be calculated. Shown below is the expanded equation for oscillating force, which depends on the motion frequency, motion amplitude of the body, frame mass, stiffness, and damping.

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

(10)

To obtain a minimal value for the oscillating force, the frame stiffness and damping coefficients have to be determined for a given frequency, frame mass, and the body’s amplitude of oscillation [6]. When the damping of the system is removed, we obtain its resonance as shown.

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

(11)

It is important to define the stiffness value where the oscillating force will remain unaffected by the damping coefficient. This quantity is defined as the optimal stiffness \( k_{\text{opt}} \), which is a function of the frame mass and motion frequency, as follows

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

(12)

This parameter, in accordance to the maximum phase shift is derived from \( \phi_m \) given in (8), with respect to the stiffness \( k \) and equating it to zero. It was observed that the maximum phase shift \( \phi_{\text{max}} \) is obtained when reaching values of optimal stiffness. The maximum phase shift is expressed as follows,

\[ \phi_{\text{max}} = \arctan \left( \frac{mc\omega}{c^2 - \frac{1}{2} m^2 \omega^2} \right) \]  

(13)

2.3. Stiffness adjustment

As the load on the backpack increases, there will be an increase in oscillation force for the same amplitude and frequency. To reduce the force, there needs to be a change in the model stiffness such that the oscillation force and phase shift remains constant. By adjusting the damper preload, the stiffness of the system can be changed. The addition of the damper preload will ensure that the values of the amplitude and the frequency have minimal deviation when there is a change in the backpack mass. Assuming a mass \( m_{\text{opt}} \), which is the average mass for highest and the lowest loading capacity for the army backpack, the \( k_{\text{opt}} \) is decided. The following equation calculates the amount preload required

\[ x_{\text{pre}} = \frac{m_1 g}{k_{\text{opt}}} - \frac{m_{\text{opt}} g}{k_{\text{opt}}} \]  

(14)

Where \( m_1 \) is the loaded weight and positive value specifies adding a preload and negative value specifies removing the preload. For applying preload to the spring, the shaft of the spring and its end plate has to be threaded. The relation between the minimum torque \( M_t \) required to add preload for the maximum load \( m_{\text{max}} \) is

\[ M_t = \frac{m_{\text{max}} d_m}{2} \tan (\phi - \alpha) \]  

(15)

Where \( d_m \) is the mean diameter of the screw, \( \phi \) is the friction angle and \( \alpha \) is the lead angle [7]. A demarcation on the frame for the optimum load height will ensure the proper preload is set on the springs by the user. The preload should be adjusted every time there is a change in the loading.

2.4. Load distribution

For the sake of estimation of the load path, average values for the frame weight and backpack load are assumed. The weight of the frame and the backpack is assumed to be around 1.2 kg and 10 kg respectively. Hence for distribution of load, the areas of the body chosen are

- Sternum
- Shoulders
- Hips
2.4.1. Sternum

The sternum is the central bone of the ribs. The distribution of load on the sternum will greatly reduce the moment which is created by the bag since most of the load will be distributed on the sternum. In the figure 1, A is the frame which will house the spring and the bag. The joints B will transmit the vertical load on the shoulders horizontally on the sternum marked in red. The strap joint D will have the hip belt attached to it. The calculated weight distribution is estimated for 112.7 N. This load is now transmitted to the sternum as the tension at the shoulders is same as the tension at the joint. Hence the entire load of the pack is now transmitted to horizontally into the body, i.e. at the sternum.

2.4.2. Shoulders

The weight of the pack is now distributed to the sternum; hence the weight on the shoulders will depend on the tension on the back-pack strap that the user has set. In the figure 2 given above, there are four plastic buckles which compensate the horizontal force at the shoulders. The weight W acts in the direction along the strap. The straps are then attached together at an angle $\theta$, which is decided by the force rating of the buckles and the average midpoint of the shoulders. The weight is then distributed to $w \cos \theta$ and $w \sin \theta$. The vertical component $w \cos \theta$ is distributed to the shoulders and the horizontal component $w \sin \theta$ is distributed to the three chest buckles and one joint which attaches the lower strap end to the bag. The buckles selected have a force rating of 20 kgs. Hence the straps will be able to take a force of $20/\sin \theta$. A triangle, as shown in the figure below, gives the angle at which the straps have to be with respect to the body. The average distance between the centre of the neck and the midpoint of the shoulders is 78 mm. The average distance between the neck and the centre of the sternum is 55mm [8]. Hence the calculated angle is taken approximately to be $36^\circ$.

2.4.3. Hips

Since the weight is distributed at the sternum using three buckles, the load on the hips is one fourth of the horizontal force on the strap. The hip strap are also used to balance the moment of the bag load. The ideal load on the sternum. The hips can carry maximum load hence it is used to carry the maximum load.

3. Design Analysis

To validate the working of the mechanism, component was designed in Solidworks. Figure 3 shows the basic design used for the testing. A W shaped frame was conceived for the sprung mass. This frame travels concentric to the main frame using linear motion bearings. The spring placed at the upper end and two dampers placed at the lower end were set for the suspension system. For testing the damping parameters of the frame, a test model was setup in MATLAB Simulink with the above calculated parameters. The setup is shown in the figure 4. After the above model was executed, the following graphs were obtained. A change in the damping amplitude is observed in figure 6 with reference to figure 5, and hence a decrease in the oscillation force is seen.
4. Conclusion
The preload adjustment reduces the excess oscillation force experienced by various loads, thus preventing the sore shoulders and the misaligned spine. The redesign of the straps also helped correct bad posture and reduce the moment of the backpack about the body. The spring damper system greatly helped in reducing the shocks of the backpack when running or jumping, thus reducing the fatigue while long strenuous walk/runs.

5. References
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