ANALYSIS OF BACKPACK RESPONSE TO TRUNK MOTION DURING LOAD CARRIAGE ACTIVITY

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A backpack vibration system consists of a backpack–human trunk system, was developed to examine the backpack's response to trunk motion when carrying a load and to determine which damping and stiffness parameters give the best result for a stable backpack vibration system. The vibration system was analysed using different values for the damping and spring coefficients in the displacement and velocity equations of the backpack vibration system. Given a backpack mass of 3.5 kg, the vibration system oscillates with a stable condition damping value of c = 2 Nsmm^{-1} and a stiffness value of k = 5 Nmm^{-1}.

KEY WORDS: biomechanical model, load carriage, external force, human motion.

INTRODUCTION: Body response to backpack vibrations has been investigated in a few studies to identify the effects of changing the pack suspension characteristics on the locomotion performance by varying the stiffness and damping coefficient in the suspension model (Ren, Jones & Howard, 2005). Ren et al.(2005) modelled a backpack suspension using cubic polynomials to describe the complex viscoelastic properties of the existing military packs. In their studies, the parameters of the suspension model were identified from dynamic test data obtained from using a hydraulically driven load carriage test-rig by Gretton and Howard (2000). A nonlinear suspension model was employed to describe the effects of different backpack suspension characteristic on the locomotion energetic by varying the stiffness and damping coefficients in the suspension model. The results show that decreasing the suspension stiffness significantly reduces the peak values of the vertical peak force acting on the torso. Foissac et al. (2009) proposed a simple characterisation of the mechanical properties of a backpack using a linear single-degree-of-freedom model to evaluate the influence of varying backpack stiffness by comparing rigid and flexible backpacks on the energetic and trunk kinematics during walking. The results show that the amplitude of the trunk is influenced by the movement of the backpack, and a flexible pack with a lower stiffness, has been shown to provide biomechanical and energy advantages.
Applying damping to a vibrating system is said to reduce the excessive vibration influenced by the motion of the structures. Thus, the identification of damping and stiffness parameters is essential for the computation of stress and strains in vibrating structures and estimating the right combination of damping and stiffness parameters in the system enables researchers to better understand the mechanical adaptations needed to produce a stable suspension system. The purpose of this study was to analyse the backpack's response to trunk motion by varying the values of the damping coefficient and stiffness in a suspension system by using the representation of a Fourier series as the excitation force during backpack load carriage activity.

METHODS: While walking with a backpack, the interaction between a pack and a human trunk occurs in a dynamic way as a result of the cyclic motion of the trunk. The motion of the backpack relative to the body causes a vibration that behaves like a spring that moves up and down following the movement of the body. As a result, a backpack suspension system is obtained and can be considered as a damped harmonic motion of a mass-spring system in which the pack is modelled as a rigid body that moves vertically with the human body. A free body diagram of a backpack suspension system is shown in Figure 1. The model consists of a backpack that attached at the back of a human trunk. F_{xp} and F_{yp} are the normal and tangential pack interface forces, respectively, M_{zp} is the pack interface moment about the pack centre of mass and u is the displacement of motion of the system.

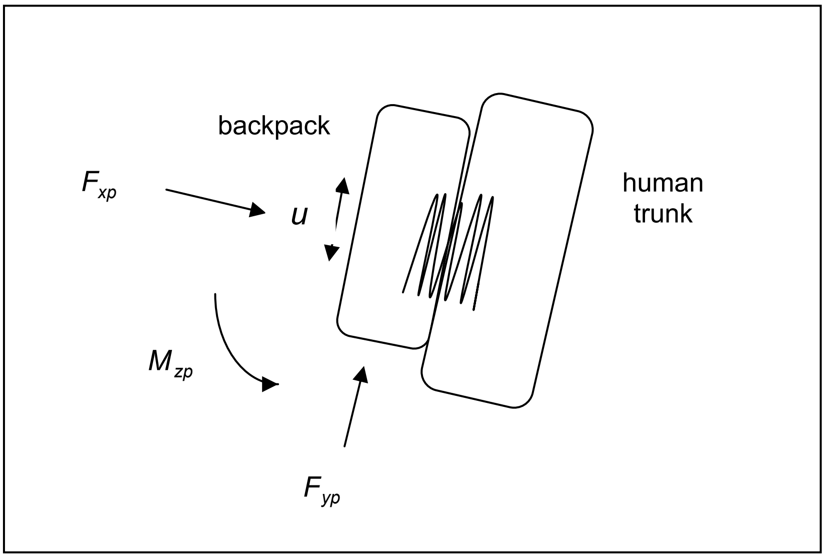


Figure 1: A free body diagram of a backpack and a human trunk showing the forces exerted on the backpack's centre of mass.

To investigate the motion of the system, the backpack is assumed to be rigid. The equation of motion of the backpack is derived as a differential equation of motion for a free vibration of a damped spring-mass system and can be written as follows:

$$\ddot{u} + \frac{c}{m}\dot{u} + \frac{k}{m}u = \sum_{n=1}^{\infty} \frac{4}{mn\pi}\sin(nt) \quad \text{for } n = 1,3,5,\ldots \tag{1}$$

where u, $\dot{u}$ and $\ddot{u}$ are the displacement, velocity and acceleration of the backpack suspension system, respectively, t is time (s), m is the mass of the backpack (kg), c is the damping coefficient ($Nsmm^{-1}$), k is the spring stiffness (Nmm^{-1}), n is the number of the selected period, and the external forces are represented by a Fourier series. Defining the parameters $\omega_o = \sqrt{\frac{k}{m}}$ as the natural frequency, $\xi = \frac{c}{2\sqrt{km}}$ as the damping ratio, the displacement of the backpack suspension system satisfies the following differential equation

$$u(t) = e^{-\zeta\omega_o t}\left(A\cos(\omega_d t) + B\sin(\omega_d t)\right) + \frac{1}{m}\left[\sum_{n=1}^{\infty} \frac{-8\zeta\omega_o n}{n\pi\pi_n}\cos(nt) + \sum_{n=1}^{\infty} \frac{4\left(\omega_o{}^2 - n^2\right)}{n\pi\pi_n}\sin(nt)\right] \quad n = 1,3,5,\ldots \tag{2}$$

Taking a first differentiation, the velocity of the backpack suspension system is derived as

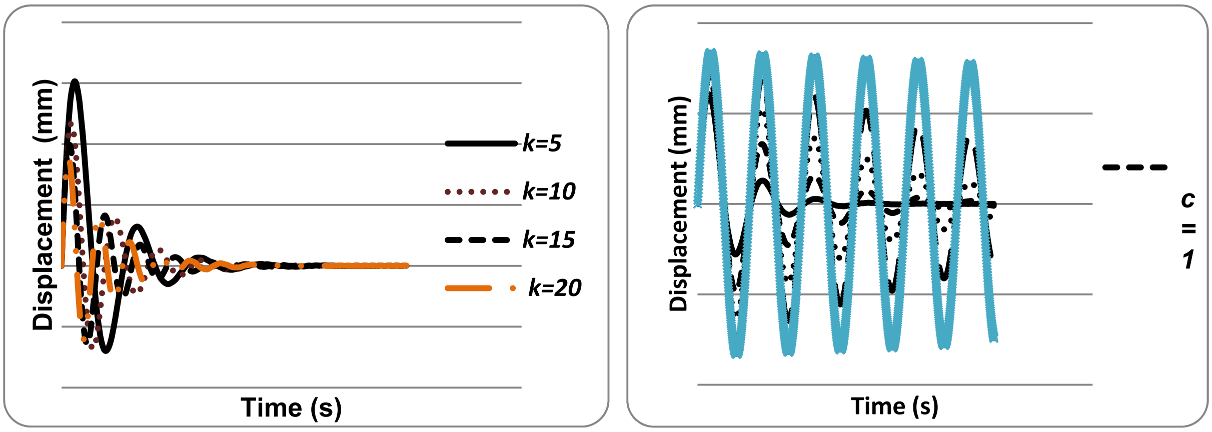
$$\dot{u}(t) = -\zeta\omega_o e^{-\zeta\omega_o t}\left[A\cos(\omega_d t) + B\sin(\omega_d t)\right] + e^{-\zeta\omega_o t}\left[-A\omega_d\sin(\omega_d t) + B\omega_d\cos(\omega_d t)\right] + \sum_{n=1}^{\infty} \frac{8\zeta\omega_o n^2}{mn\pi D_n}\sin(nt) + \sum_{n=1}^{\infty} \frac{4n\left(\omega_o{}^2 - n^2\right)}{mn\pi D_n}\cos(nt), \quad n = 1,3,5,\ldots$$

where,

$$D_n = (2\zeta\omega_o n)^2 + \left(\omega_o{}^2 - n\right)^2. \tag{3}$$

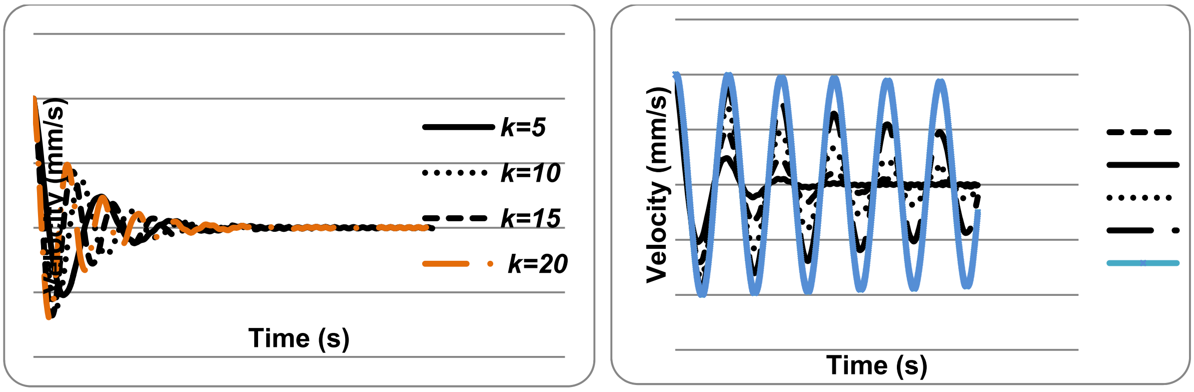
In this study, the mass of the backpack was chosen to be 3.5 kg, while various degrees of damping and stiffness coefficients were used to determine the best values for a stable vibration system. Under the initial conditions $u(0)=0$ and $\dot{u}(0)=1$, the fourth-order Runge-Kutta algorithm was used to solve equations (3) and (4) numerically with a time step of 0.02.

RESULTS: The solution of the displacement of motion in this study was a summation of the transient solution and the steady-state solution induced by the Fourier series as the external force. The simulation results for different damping and stiffness coefficients are depicted in Figure 2 and 3.



(b)

Figure 2: Displacement of the backpack suspension system with (a) *c* = 2 and various degrees of stiffness coefficients, (b) with *k* = 2 and various degrees of damping coefficients.



(b)

Figure 3: Velocity of the backpack suspension system with (a) *c* = 2 and various degrees of stiffness coefficients, (b) with *k* = 5 and various degrees of damping coefficients.

DISCUSSION: The graph of displacement of the backpack suspension system in Figure 2(a) shows that, for a constant value of damping coefficient, the values of the pack motions *u* decrease as the stiffness *k* increases from 5 to 20. Although the period of oscillation decreases as *k* increases, the system vibrates with a higher frequency before decaying to zero. In Figure 2(b), for a constant value of spring stiffness, the displacement of the backpack suspension system shows the same period of oscillation for different values of the damping coefficient. Decreasing the damping coefficient will increase the motion of the backpack suspension system. However, the amplitude of the largest value of damping coefficient, *c* = 2, decays to zero faster than do the smaller values.
Figure 3(a) shows that, for a constant value of damping coefficient, the amplitude becomes larger as the stiffness values increase. However, the period of oscillation decreases, and in contrast, the value of the frequency increases before it decays to zero.
The graph of the velocity of the backpack suspension system in Figure 3(b) shows that, for a constant value of spring stiffness, the periods of oscillation for all damping coefficient values are similar. Decreasing the damping coefficient from 2 to 0.02 increases the velocity of the

backpack suspension system. However, the amplitude of a large value of the damping coefficient decays to zero faster than that of smaller values.
The simulation results show that, within the range of different damping and stiffness coefficients, changes in the damping coefficient had a stronger changing effect on the amplitudes of the displacements and the velocities of the suspension system than on stiffness. However, in both the displacement and velocity of the backpack suspension system, it was shown that, by taking the smallest value of spring stiffness, k = 5, and the largest value of damping coefficient, c = 2, the system decays fairly quickly just after 15 seconds. However, with k = 5 and c = 1, the system only decays to zero after 30 seconds. Nonetheless, other smaller values of the damping coefficient make the system vibrate more rapidly and thus take more time to reach equilibrium. Therefore, the results indicate that the vibration system for both displacement and velocity oscillates with a stable condition damping value of c = 2 and spring stiffness of k = 5.

CONCLUSION: With the values of c = 2 and k = 5, the simulation results for the displacement, velocity and acceleration of the backpack suspension system can be applied to the biomechanical model of a backpack load carriage (AbdulRahman, Rambely & Ahmad, 2009) in order to determine the changes in joint forces and moment exerted on the human trunk while walking with a backpack.

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