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Dynamics of carrying a load with a handle suspension

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ABSTRACT

Carrying loads with a compliant pole or backpack suspension can reduce the peak forces of the load acting on the body when the suspension natural frequency is tuned below the stepping frequency. Here we investigate a novel application for a load suspension that could be used to carry a load by hand, which is a common yet difficult method of load carriage and results in inherently asymmetric dynamics during load carriage. We hypothesize that the asymmetric dynamics of carrying a load in one hand will result in multiple locomotion frequency modes which can affect the forces of carrying a load with a handle suspension. We tested an adjustable-stiffness hand-held load suspension with four different natural frequency values while walking and running compared to a rigid handle. As expected, the peak forces acting on the body decrease compared to a rigid handle as the effective suspension stiffness decreases below the stepping frequency. However, the asymmetric dynamics of carrying a load with one hand introduce another frequency mode at half the stepping frequency which increases the peak forces acting on the body when the natural frequency of the handle is tuned near this frequency. We conclude that hand-held load suspensions should be designed to have a natural frequency below the half-stepping frequency of walking to minimize the peak forces and the musculoskeletal stress on the human body while carrying loads with one hand.

1. Introduction

In some Asian cultures, compliant bamboo poles are used to carry heavy loads. Kram (1991) investigated the effect of using compliant poles on human running and found that compliant poles reduced the peak shoulder forces, peak vertical ground forces, and loading rates compared to a typical backpack.

More recently, a backpack was developed that suspends a load with highly compliant elastic bands (Rome et al., 2006). The suspended load backpack reduced the peak accelerative forces acting on the body during walking by 82% and also reduced the metabolic cost of walking by 6.2% (Rome et al., 2006). The peak accelerative forces of the load acting on the body during running were reduced by 86% (Rome et al., 2006). Foissac et al. (2009) developed a stiffer backpack suspension which significantly increased the peak forces acting on the body compared to a stiffly-attached load because the natural frequency of the load suspension was tuned to be close to the resonant stepping frequency of walking.

Carrying heavy loads by hand is one of the most difficult and least efficient means of load carriage (Datta and Ramanathan, 1971; DeVita et al., 1991; Malhotra and Gupta, 1965), yet heavy loads such as briefcases, infant car seats, shopping bags, tool boxes, stretchers, and emergency equipment are frequently carried by hand. Like a backpack suspension, a handle suspension that could reduce the peak forces acting on the body may offer a better way to carry hand-held loads with less musculoskeletal stress and fatigue.

The design of a handle suspension may be similar to the design of a suspended backpack in many ways. However, hand-held loads are often carried unilaterally on one side of the body, which can affect the asymmetric lateral motion of the trunk (Crosbie et al., 1994; DeVita et al., 1991; Fowler et al., 2006) and the sinusoidal frequency components of the body center of mass motion (Crowe and Samson, 1997; Crowe et al., 1993). Here, we seek to determine how the asymmetric dynamics of carrying a load in one hand while walking and running with a handle suspension of variable stiffness could affect the peak forces of the load acting on the body.

We hypothesize that

H1. The dynamics of carrying a load with one hand will be characterized by a stepping frequency and a half-stepping frequency due to the inherent asymmetry of using one hand to carry a load (Crowe and Samson, 1997; Crowe et al., 1993.

H2. The peak forces acting on the body will decrease when the natural frequency of the handle is reduced below the stepping frequency because the load suspension behaves like a vibration isolator (Hoover and Meguid, 2011; Rome et al., 2006).

H3. The peak forces acting on the body will increase when the natural frequency of the handle suspension is tuned near the stepping and

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half-stepping frequency. Prior work showed that a suspended backpack with a natural frequency tuned near the resonant stepping frequency of walking significantly increased the peak forces acting on the body compared to a stiffly-attached backpack (Foissac et al., 2009). We expect that the peak forces acting on the body will similarly increase if the natural frequency of a handle suspension is tuned near the stepping or half-stepping frequency.

H4. The vertical displacement of the lower back, shoulder, and hand will be reduced when the load suspension is tuned near the primary or secondary stepping frequency mode. Foissac et al. observed a similar reduction in the motion of the torso when a backpack suspension was tuned near the resonant walking frequency.

To test these hypotheses, we used a Discrete Fourier Transform (DFT) algorithm to analyze the amplitude and frequency components of the load forces acting on the body. We expect that this study will enhance our understanding of locomotion with elastically-suspended loads and could specifically enable the design of new suspension mechanisms for carrying hand-held loads.

2. Methods

2.1. Variables

The independent variables in this study were the handle suspension stiffness and the type of locomotion (walking and running). The dependent variables in this study were the peak forces acting on the body and the vertical displacement of the load, lower back, shoulder, and hand.

2.2. Experimental approach

Written informed consent was obtained from six young men to participate in this IRB approved study. Their average ± SD age, mass, and height were 21.5 ± 2.8 years, 70 ± 8.7 kg, and 1.78 ± 0.04 m, respectively. Our study was limited to a sample size of six subjects. As shown in Section 3, we were nonetheless able to find several statistically significant results to test our hypotheses. The subjects walked at 1.34 m/s and ran at 2.24 m/s on an instrumented treadmill (Bertec Corporation, Columbus, OH) for two minutes while using four different handle suspensions and a rigid handle to carry a 7.11 kg load. The experiments were counter-balanced such that half of the subjects started with the rigid handle and then used increasingly compliant handles while the other half did the opposite. All subjects were right-handed and carried all handles in their right hands.

We considered a single relatively fast walking speed of 1.34 m/s (the approximate average walking speed used in Foissac et al. (2009)) because load suspensions tend to work best at relatively fast walking speeds and stepping frequencies. We considered a single running speed of 2.24 m/s because this was found to be the fastest comfortable running speed for most subjects while carrying a load that could be sustained over multiple two-minute sessions. The walking and running speeds were fixed to maintain an approximately constant stepping frequency for all subjects.

In general, this study was designed to test how using a handle suspension would compare to a rigid handle under practical conditions that represent a realistic user adoption scenario. We sought to test how varying the handle suspension would affect the whole system, including the effects on the mechanical design due to the slightly increased weight of the suspension and the behavior of human locomotion. Therefore, we preserved the mass differences between the handle suspensions and the rigid handle (Table 1) because reducing the effective suspension stiffness required additional mechanical structure that added distributed weight in the mechanism. Further, subjects were not instructed on how they should move their arms.

A Vicon motion capture system with six T-160 cameras (Oxford Metrics Group, Oxford, UK) was used to capture the dynamics of the right side of the body at 120 Hz. The Vicon markers were placed on the small of the lower back, the right head of the humerus, the 3rd metacarpal of the right hand, and the load. A 222.4 N load cell and amplifier (LSB302 and CSG110, Futek Advanced Sensor Technology Inc., Irvine, CA) were used to measure the reaction forces between the handle and the load suspension (sampled at 1200 Hz).

2.3. Data processing

The data was post-processed using Matlab (Mathworks, Natick, MA) using a zero-phase 3rd order butterworth low-pass filter with a cutoff frequency of 6 Hz. The discrete Fourier transform (DFT) algorithm in Matlab was used to estimate the frequency and amplitude content of the dependent variables in each two minute data set. For the DFT analysis, a high-pass digital butterworth filter with a lower bound of 0.5 Hz for walking and 0.75 Hz for running was used to remove the average offset and low-frequency noise.

The average absolute peak forces were calculated by averaging all of the maximum peaks in the transient load cell force data. The amplitude and frequency content of the load forces acting on the body were determined by finding the maximum amplitudes from the DFT analysis of each trial. The same approach was used to calculate the amplitude and frequency content of the vertical displacement of the lower back, shoulder, and hand. To validate the DFT analysis, the frequency content was compared to the stepping frequency f, which was determined by calculating the average time period between N successive peaks $(t_{N+1}-t_N)$ from the transient vertical displacement of the lower back during each trial

$$f=\frac{1}{N}\sum_{1}^{N}\frac{1}{t_{N+1}-t_N}. \tag{1}$$

Table 1
The mass of each handle configuration. The mass difference between the rigid handle and the handle suspension with a triple cantilever pair was 1.02 kg, or 13.7%. This mass difference resulted from adding three pairs of cantilever spring steel strips and their associated clamps to change the effective stiffness of the handle suspension. This additional mass was distributed throughout the compliant, long travel spring structure. An equivalent amount of mass could have been added to the load mass to account for the mass differences between each handle, but we did not believe this was a fair comparison due to the distribution of mass throughout the structure. We would need a different handle suspension mechanism to maintain an equally distributed mass for each handle. Therefore, we neglected the differences in mass between the handles in the current study. While this may be viewed as a potential shortcoming of the current study, this approach has the strength of representing the realistic mass increases associated with mechanisms that have lower effective stiffness values and longer spring travel lengths.

Configuration	Mass (kg)
Load only (weights and mount)	7.11
Handle and load cell mount	0.34
Rigid handle	7.46
Handle suspension with a single cantilever pair	7.78
Handle suspension with a double cantilever pair	8.10
Handle suspension with a triple cantilever pair	8.48

2.4. Statistical analysis

Results are presented as mean ± SD in the text and figures. A one-way ANOVA was used to test for the effect of the handle suspension natural frequency on the following dependent variables: absolute peak load force, the amplitude and frequency components of the dynamic load forces, and the vertical displacement of the lower back, shoulder, and hand. When a significant effect was detected, the normality and variance homogeneity ANOVA assumptions were checked and post-hoc Tukey tests were calculated using SPSS (IBM, Armonk, NY) with a standard significance level of $\alpha=0.05$ (see Supplementary materials). The data for walking and running were considered separately.

2.5. Handle suspension design

The handle suspension was designed to vary the natural frequency over a range of values below an approximate walking frequency of 2 Hz. To achieve this, we used pairs of 2.54 cm wide and 0.081 cm thick 1095 spring steel strips to suspend a load from a handle. The length of these cantilevers could be adjusted by moving aluminum plates to clamp the strips at different positions, enabling the natural frequency of the suspension to be rapidly changed between experiments (Fig. 1).

To reduce the nonlinear stiffening effect of the cantilever suspension due to large beam deflections, multiple sets of cantilevers pairs were connected in series to decrease the deflection of each cantilever and the effective stiffness of the structure (Fig. 2). The overall weight of each handle configuration is shown in Table 1.

2.6. Effective stiffness characterization

The effective stiffness of the cantilever suspension was measured at various lengths for one, two, and three cantilever pairs by attaching the suspension with the 7.11 kg load to a rigid frame and physically perturbing the load. The load cell and amplifier were used to measure the reaction forces between the handle and frame sampled at 1200 Hz using the Vicon system for 30 s. The damping ratio and damped natural frequency for each suspension configuration with varying cantilever lengths