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Research paper

Energy performance analysis of a backpack suspension system with a timed clutch for human load carriage

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A B S T R A C T

This work theoretically investigates methods of reducing the energetic cost of bipedal walking while carrying a backpack with a suspension system. We extend a previous 2DOF model proposed by Ackerman and Seipel (2014) by adding a timed clutch to the suspension mechanism. The clutch allows the mechanism to switch between states of elastic or rigid connection of the backpack and the body. Periodic switching between the two states of the mechanism is either event-based or timing-based, and may result in inelastic impacts. We study the hybrid dynamics induced by the action of the clutch mechanism, analyze energy expenditure and stability of periodic solutions, and seek for optimal values of stiffness and switching times that minimize the energetic cost. It is found that in many cases, the clutch mechanism can significantly reduce energy expenditure compared to both rigid and elastic suspensions.

1. Introduction

Walking while carrying loads has been a commonly performed task since early human history. Traditional farmers, outdoor hikers, combat soldiers, technical maintenance staff, search-and-rescue and medical crew, are all required to carry heavy loads for long distances [1–3]. Carrying loads during legged locomotion is an energy consuming task, where the energetic cost is influenced by various factors such as weight, walking speed, and slope [4–7]. Many attempts have been made to reduce the energetic cost of laden walking, for improving life quality, durability and effectiveness of the various carrying tasks mentioned above. Carrying a load using elastic elements is an ancient strategy, as implemented in the "milkmaid's yoke" and other carrying poles of Asian farmers [8]. Experimental measurements have shown that using carrying poles results in noticeable reduction in muscular loads and ground reaction forces, but not in energy saving [9]. On the other hand, it is known that elastic energy storage in muscles and tendons plays an important role in energy efficiency of animal locomotion [10]. In the recent decades, various systems of elastic suspension for carried backpacks have been developed and tested [11,12]. Later works have presented theoretical analysis of carrying elastically suspended loads. The work [13] analyzed the influence of elastically-suspended backpack on the dynamic load acting on the body. The recent work of Ackerman and Seipel [14] has presented a simple theoretical model of the human-backpack dynamics as a two-mass system, where the vertical oscillations of the human's center of mass during walking are actuated by an external harmonic input of "effective leg length". This model has been utilized in [14] in order to analyze the mechanical energy expenditure and comparing it to experimental measurements of backpack suspension systems [11,12]. It has been found in [14] that the theoretical model

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analysis can be useful for cleverly choosing suspension system parameters in a way that results in reduction in energy cost of laden walking.

The use of passive elastic elements for assisting legged locomotion has recently become increasingly attractive [15,16] and particularly the design of wearable devices, either for healthy humans [17–19], rehabilitation [20–22] or amputees' prosthetics [23]. These wearable devices often include a combination of springs and timed clutches [18,19,24] or brakes [22]. Timed engagement and release of clutches can be utilized in order to disconnect the spring during leg swing [19,20], trigger a mechanical damper at knee joint [17], or change the foot-ankle impedance during walking gait, from a soft spring to a stiff bumper [25]. The combination of timed clutches and springs induces a multi-modal dynamics for different stages of the periodic gait, and it has been shown that such systems can be designed in clever ways that reduces the overall energetic cost of walking. In spite of the remarkable success of this concept for wearable walking assistance devices, incorporating timed clutch mechanisms into a backpack suspension system has not yet been studied.

The goal of this work is to theoretically study the effect of adding a timed clutch into a backpack suspension system on potential saving in energetic cost. We use the simple model studied in [14], which describes the vertical motion of the human and backpack through a system of two masses connected by springs and dampers and actuated by a harmonic base excitation. The clutch is represented by time-periodic switches between two states of the connection between the masses, from a spring-damper element to a rigid constraint and vice versa. Two possible switching laws are considered. The first law is based purely on timing, and thus it involves an inelastic impact that instantaneously stops the relative motion between masses. The second switching law is based on event detection that locks the connection without impact, when the relative velocity crosses zero. Both switching laws induce hybrid dynamical systems whose solutions involve non-smooth transitions. We find periodic solutions for these systems and analyze their orbital stability. Then we compute the energy expenditure over a non-smooth periodic solution, and study its dependence on switching times of the clutch. We numerically optimize the timing parameters and suspension stiffness, for achieving minimal energetic cost. The theoretical analysis proves that adding the clutch and cleverly choosing its timing can result in significant reduction in energetic cost of laden walking, and also in improving robustness of the suspension system's performance with respect to changes in task conditions such as load and walking speed.

2. Problem statement and formulation

We now review the simplified theoretical model of the backpack suspension system presented by Ackerman and Seipel [14], discuss our addition of a clutch, and formulate the system's dynamic equations. The model in [14] represents the suspension using a two-mass system that move in vertical direction, as shown in Fig. 1. The model has two degrees of freedom:the vertical translations of the body $y_1(t)$ and of the backpack $y_2(t)$. The masses of the body and the backpack are m_1, m_2, respectively. The dynamics of the legs [26] is represented by linear stiffness k_1 and damping c_1 and a periodically-varying "effective length" $L(t)$, which is regarded as the input of the system. Its value is given as a harmonic function: $L(t) = A\sin(\omega t)$, where the frequency ω is determined from the mean walking speed [27]. The backpack is connected to the body via a suspension system with linear stiffness k_2 and damping c_2. Nominal values of the system's physical parameters, which are taken from [14], appear in Table 1. In particular, values of the suspension system parameters k_2, c_2 are adapted from the experiments in [11]. The dynamic equations of the system are given

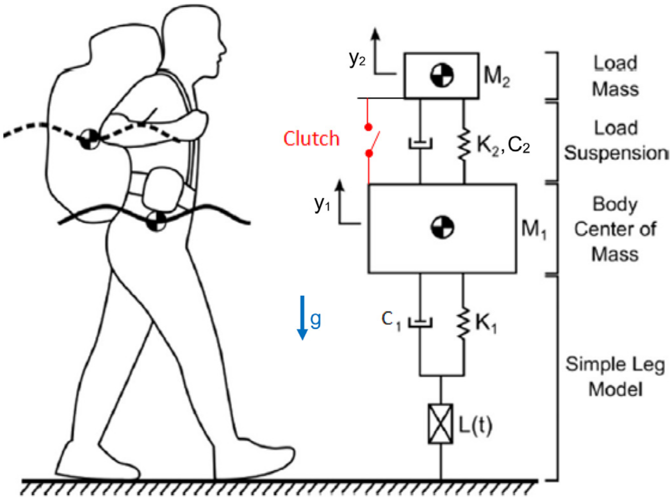

Fig. 1. The simple model from [14] of a walker with a suspended backpack.