Analysis of passive wearable spring-clutch device for energy saving during walking

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Summary. There is a growing interest in wearable devices for energy saving during laden walking, with applications to civil hiking or military soldiers walking with heavy loads in outdoor rough terrains. Recent works presented semi-passive elements based on springs engaged by timed clutches. In this work, we analyze the hybrid dynamics induced by a spring-clutch model and study optimization of spring parameters and clutch timing for minimizing mechanical or metabolic energy expenditure. We consider two simple models: one-dimensional oscillations of a backpack suspension system, and planar walking gait of a five degrees-of-freedom human-like model. We show that springs and timed clutches can, in theory, lead to a drastic reduction in energy saving.

Load carrying while walking on a rough terrain is an important task performed often by hikers, soldiers and workers. Carrying a load causes increased metabolic cost while walking. Several works presented robotic exoskeletons which are augmented on the human body and actuated by motors [1,2]. These are typically cumbersome and heavy, and require excessive energy expenditure, where power resources must be carried by the users. On the other hand, recent compact and wearable semi-passive devices have been developed, which are mainly based on energy storage and release by an elastic spring element [3]. The work [4] have presented a device mounted on the ankle joint, which contains a timed clutch mechanism that engages a tension spring during stance phase, and releases the spring at its unloaded state during leg swing. This device results in 7% saving in metabolic energy expenditure compared to free walking. Nevertheless, it is proposed here that energy efficiency can be further improved by considering a clutch arrangement that locks the spring at a loaded state with stored energy, and releases it at a different time when mechanical power is needed. In this work, we study the hybrid dynamics induced by such a mechanism of a spring and timed clutches, analyze mechanical and/or metabolic energy expenditure during a walking gait, and optimize the spring and timing parameters for achieving maximal energy saving. We consider two simple models of dynamic walking, as detailed next.

The first model, which has been proposed in [5], considers energy performance of a spring-damper suspension system of a backpack during human walking. The model, shown in Figure 1(a), studies the one-dimensional vertical motion of two masses representing the human and backpack, where the periodic walking is represented by a harmonic excitation of the "effective length" of the leg $L(t)$. Combining analysis of the system's linear dynamics and experimental results from [6,7], it is shown in [5] that the suspension system can reduce the mechanical energy expenditure at the "effective leg". In our work, we analyze the system's performance under a timed clutch added in parallel to the spring-damper suspension between the body and the backpack. The clutch is released at a desired time during the walking period. We consider two possible laws of switching the clutch back to locked state: the first is based on a chosen timing and typically results in an (inelastic) impact event where the relative velocity $\dot{z}_1 - \dot{z}_2$ instantaneously jumps to zero. The second switching law occurs at the event of zero relative velocity $\dot{z}_1 = \dot{z}_2$, and thus it involves no impact, though it requires sensing of the relative velocity. We study periodic solutions of the hybrid dynamics under the two switching laws, and analyze their orbital stability by computing the linearization eigenvalues of the Poincaré maps' Jacobian matrices, which are obtained analytically. It is shown that periodic solutions under the timing-based switching law always possess global asymptotic orbital stability, whereas the event-based switching law can result is unstable solutions. Next, we study the influence of spring stiffness, clutch timing and switching law on the energy expenditure. We find that the event-based switching law can result in significant energy saving compared to states of fully locked or fully free spring, for the physical parameter values in [5]. Additionally, we find that global energy minimum in switching times in obtained at zero-impact switching, whereas constrained optimization where one switching time is prescribed typically result in minimal energy under non-zero impact switching. Finally, we find the optimal spring stiffness and show that it gives minimal energy expenditure without using clutch locking, whereas for non-optimal stiffness the clutch timing does result in reduced energy.

In the second part, we consider a simplified planar model of human walking, which consists of five joints and point feet, see Figure 1(b). We use fitted data of gait trajectories for joint angles, adapted from [8]. We consider an arrangement of two clutches, one in series and one in parallel to the spring, see Figure 1(c). This enables using an additional state where the spring is locked and stores energy while the device's endpoints can move freely. During motion, we analyze switching between this latter state and the state where the spring is engaged, when the device is mounted around the knee joint, see Figure 1(b). We consider *metabolic energy cost*, which accounts for muscles' function and their incapability of energy regeneration by using Margaria's model [9], which assigns different energetic efficiencies for positive and negative work. First, we optimize the spring's stiffness and free length without clutch switching, and find optimal values that save more than 30% of metabolic cost compared to walking without a spring. Next, we optimize the timing of locking and releasing the spring, and obtain further reduction of more than 20% in metabolic cost. Despite the model's simplicity, these findings give an indication on the potential utility of this spring-clutches arrangement for energy saving during human walking. Future works will consider more detailed models that account for ankle joint and foot-ground contact transitions, as well as the influence of load carrying.

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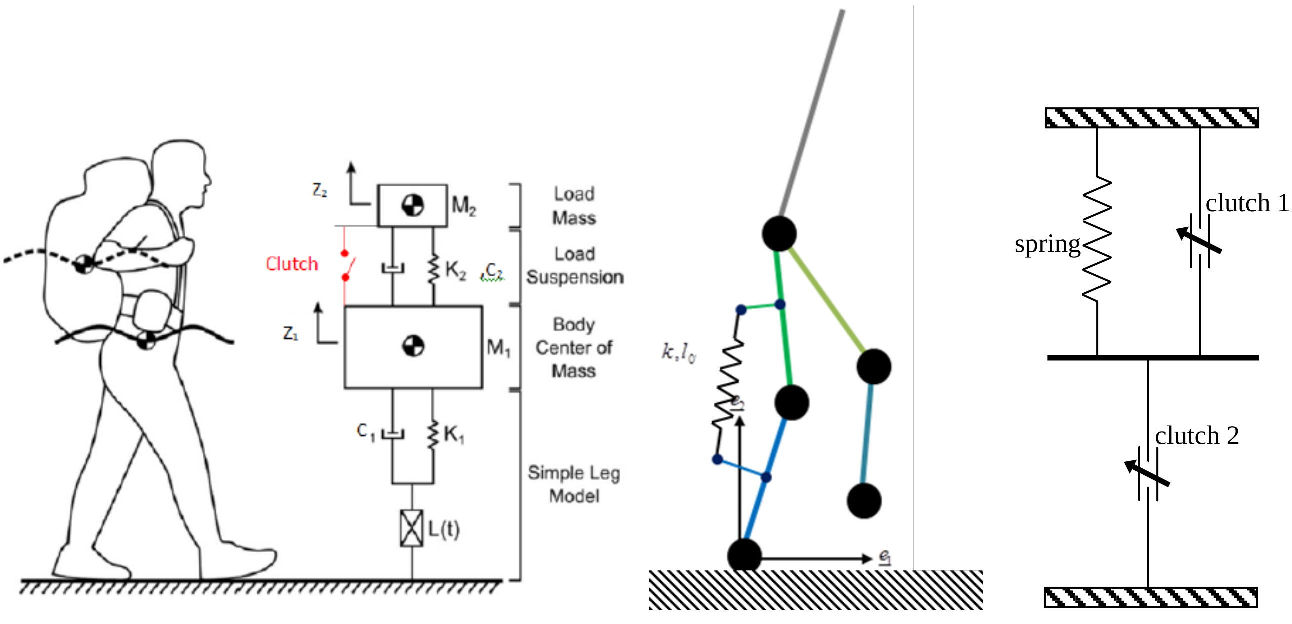

(a) (b) (c)

Figure 1 – (a) The one-dimensional model of human-backpack suspension [5]. (b) Planar 5-DOF model of human walking. (c) Two-clutch-spring device.