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Necessary condition for forward progression in ballistic walking

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Ballistic walking requires an appropriate configuration of posture and velocity at toe-off to avoid backward falling. In this study, we investigated a determinant of the state of the body center of mass (COM) at the toe-off with regard to ballistic walking. We used an inverted pendulum model to represent ballistic trajectories and the necessary condition for forward progression by a simple relationship between the COM states (position and velocity) at toe-off. This condition was validated through a computer simulation of a 7-link musculoskeletal model and measurement experiments of human movements involving stepping and walking. The results of the model simulation were in good agreement with some of the results predicted by the inverted pendulum model. The measurement experiments of walking and stepping movements showed that most COM states at toe-off satisfied the condition for forward progression and the measured trajectories during single support phase were similar to the ballistic trajectories although humans are capable of walking in non-ballistic ways. These results suggested that the necessary condition for forward progression can predict the COM states at toe-off for efficient movement and for avoiding backward falling during single support phase.

1. Introduction

The human walk is characterized by excellent efficiency and stability. It is interesting how the central nervous system (CNS) determines a gait pattern with an appropriate balance between efficiency and stability. For various combinations of gait velocities and stride length, a human walks using a

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preferred combination in which the metabolic energy cost is minimum (Elftman, 1966; Zarrugh, Todd, & Ralston, 1974). The fluctuation in the vertical center of mass (COM) during walking is a functional movement that converts potential energy into kinetic energy and vice versa (Cavagna & Margaria, 1966). The conservation of kinetic and potential energies aids in minimizing the metabolic energy cost. Recent studies showed that minimizing the vertical COM movement leads to an increase in the metabolic cost (Gordon, Ferris, & Kuo, 2009; Ortega & Farley, 2005). Mochon and McMahon (1980) analyzed ballistic walking patterns that simulate movements during single support phase in the absence of active joint torque, under the assumption that muscles act only during the double-support phase (Basmajian, 1976). They showed that the ballistic trajectories using appropriate initial postures and velocities were similar to the trajectories of preferred walking.

Extending the ballistic walking, McGeer (1990) demonstrated a model that could walk down a slight slope without any actuators, which is called passive dynamic walking. The passive dynamic walking pattern is similar to the human walking pattern, which suggests that a determinant of human walking depends on the passive dynamics of the leg mechanism. Although the completely passive walker could not walk on level ground because there is no compensation for the energy lost in the foot-floor collision, Collins, Ruina, Tedrake, and Wisse (2005) demonstrated that biped robots based on passive dynamic walking could walk on level ground using small amounts of power. Based on the passive dynamic walking, Kuo, Donelan, and Ruina (2005) proposed that the major determinant of the metabolic cost of walking is a redirection of the COM during the double support phase. The inverse dynamics analysis of a musculoskeletal model revealed that there was significant positive power in the ankle joint of the hind leg during the double support phase (Winter, 2005). It appears that the CNS controls the configuration of the posture and its velocity at the toe-off for the following efficient movement.

The ballistic walking mechanism requires an appropriate posture and velocity at the toe-off. When the energy produced during the double support phase is very high, the negative work done during the single support phase detracts from efficiency. On the other hand, when the energy produced is low, additional energy input from the stance hip torque is required (Lewis & Ferris, 2008). Kuo (2002) analyzed a powered walking model and showed that using hip extension moment alone to propel the COM forward is more energetically expensive than using a toe-off impulse. Furthermore, a low COM velocity might result in backward falling (Hof, Gazendam, & Sinke, 2005; Pai & Patton, 1997). Yang, Anderson, and Pai (2007) used a musculoskeletal model with active joint torque to obtain the minimum threshold of the COM state (position and velocity) that was required to avoid falling backwards. Their model could accurately predict the boundary of backward falling of measured slipping movement (Yang, Anderson, & Pai, 2008). On the other hand, COM states measured during walking at the toe-off showed a large margin for the minimum threshold to avoid backward falling. It can be presumed that COM velocity considerably larger than the threshold is required to achieve the movement using less effort.

The aim of this study was to elucidate the determinant of the COM state at the toe-off for forward progression. We analyzed the COM trajectories of human bipedal walking based on the "Linear inverted pendulum mode" theory by Kajita and Tani (1996), which provides prediction and control to bipedal robots on rugged terrain as well as push recovery (Pratt, Carff, Drakunov, & Goswami, 2006; Rebula, Cañas, Pratt, & Goswami, 2007). In the present study we show that a necessary condition for forward progression in ballistic walking is given by a simple relationship between the COM position and velocity. First, we examine the necessary condition using a 7-link musculoskeletal model. Second, we compare the measured COM trajectories for natural speed walking and for stepping movements with various step lengths with those estimated by the inverted pendulum model, as shown on the phase portrait. Changing the step length results in a change in the COM position at toe-off; therefore, the dependence of COM velocity on the COM position is evaluated. In addition, we compare the COM trajectories for walking with those for stepping, in order to evaluate the effects of the COM position on different values of COM velocity at toe-off. We expect the necessary conditions for stepping to be more stringent than those for walking.

2. Necessary condition for ballistic walking

We analyzed the ballistic COM trajectory by applying a linear inverted pendulum model during the single support phase, as proposed by Kajita and Tani (1996). As shown in Fig. 1A, the COM is regarded