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Level-ground walking for a bipedal robot with a torso via hip series elastic actuators and its gait bifurcation control

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HIGHLIGHTS

- A level-ground walking method for a bipedal robot with a torso is proposed.
- Hip SEAs support the torso as well as complement energy via elastic potential energy.
- Our simple control scheme can lead to an efficient and natural stable period-1 gait.
- A variety of bifurcation gaits are observed, many of which never reported before.
- Bifurcation gait can be controlled to period-1 gait, which has better performance.

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ABSTRACT

Recent studies have shown that a bipedal robot with a torso supported by springs on the hip can have a stable passive gait on a slope, while such a robot walking on level ground is a new challenge and has rarely been studied. This research adds actuators in series with the springs to form series elastic actuators on the hip and applies a state machine as controller to achieve stable walking on level ground. During walking, hip series elastic actuators support the torso from the legs as well as complement the energy to the system via elastic potential energy. The state machine uses the landing impact of the swing leg and the actuation durations as events to make the robot switch between successive active and passive walking processes. Because this simple scheme makes full use of the dynamics of the robot, it can lead to an efficient and natural gait. By means of numerical simulation, in addition to the stable period-1 gait, we found a variety of gait bifurcation phenomena, including the period-doubling bifurcation, the Neimark–Sacker bifurcation, the Neimark–Sacker-2 bifurcation, the period-X bifurcation, and the Neimark–Sacker-X bifurcation, among which many types have never been reported in previous studies. We also show that the unstable period-1 gait embedded in the bifurcation gait can be stabilized by applying the Ott–Grebogi–Yorke method. Not only can the gait bifurcation be suppressed, but also higher gait performance can be achieved.

1. Introduction

Since ‘passive dynamic walking’ was introduced by McGeer [1] in the late 1980s, the torso has been abolished in walking models. However, recently, a growing number of researchers have turned their attention to bipedal walking robots with torsos, which are more human-like. In addition, adding a torso to a robot has practical benefits, such as allowing more manipulations or interactions by installing arms or a head, and holding electronics or batteries in the trunk. Investigating more about walking with a torso may improve the application of the bipedal robot. In 2000, Chatterjee et al. [2] proposed a possible solution: adding a torso to the passive bipedal walking model via hip springs, but they did not realize it. In 2005, using this model, Gomes et al. [3] succeeded in realizing collision-less walking on level ground in simulation, however, such a gait with exaggerated unnatural movement was quite different from human gait and was also unstable, which made it lack practicability. In 2011, Chyou et al. [4] continued to work on this model. They presented stable passive gaits on a slope and showed that the stability and efficiency can be improved with a torso via springs. In 2012, the authors [5] found that two stable period-1 gaits can co-exist with certain model parameters. Farshimi et al. [6] also showed multiple routes to chaos in the passive gait of the simplest walking model with a torso added via hip springs. The above results demonstrate that hip springs can help in passively adding a

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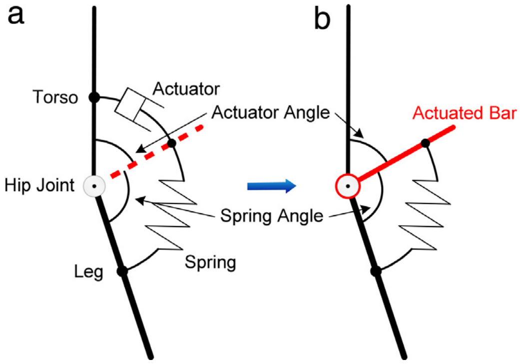

Fig. 1. Schematics of the hip series elastic actuator.

torso to a bipedal walking robot, and such a robot can realize stable passive walking on a slope. However, level-ground walking using this model is a new challenge and an important issue for its practical application, which has rarely been studied yet. If suitable actuations are added, the level-ground walking gait will be efficient and natural compared with those robots controlled by high-gain control, which motivates us to go ahead with the research. This study makes further use of the hip springs to achieve stable level-ground walking: specifically, it uses series elastic actuators as hip actuators and a state machine as a controller.

Using series elastic actuators for hip actuation is inspired by the human hip structure. There are natural elastic actuation structures in the human hip: the muscle–tendon unit, including the hip extensor—gluteus maximus; and the hip flexors—iliacus and psoas [7,8]. Both of these act on the hip joint antagonistically, stabilizing the torso and protracting and retracting legs during walking. In the muscle–tendon unit, the muscle acts as an actuator and the tendon can be modeled as a passive elastic element [8]. Because under most normal walking conditions, the tendon can be seen as a linear spring [9], and because the elasticity of the muscle fiber is insignificant compared with that of the tendon [10], the antagonistic muscle–tendon units at the hip can be imitated by an actuator in series with a linear spring, whose structure is similar to the MIT series elastic actuator introduced by Pratt et al. [11]. Various SEAs have been successfully applied in bipedal robots and prostheses [12–16], and they usually use a force/torque control mode. In this research, the springs are used as potential energy storage devices to replenish the system energy and realize level-ground walking. The actuator in the SEA deforms the spring to regulate its elastic potential energy.

The hip SEA in this study is shown as (a) in Fig. 1. It is mounted between the torso and the leg. The actuator is installed on the torso and its output is connected to one end of the spring. The other end of the spring is attached to the leg. The actuator can make a bi-directional movement, i.e., the spring can be compressed or stretched. To facilitate understanding in the later part of the manuscript, the output of the actuator, i.e., the actuator angle in Fig. 1, will be represented by the red actuated bar as shown in (b). The output torque is determined by the deformation of the spring, namely the difference between the spring angle in Fig. 1 and the equilibrium angle of the spring.

Many active control methods to realize level-ground walking in a bipedal robot with a torso exist, and act to control the torso posture [17–21], control the relative angle between the torso and the stance leg [22], or directly track a reference posture trajectory [23,24]. These methods rely on high-gain feedback control, which damages the passive dynamics of the robot, resulting in inefficient and unnatural gaits. Furthermore, these methods produce high demand on the model fidelity and the actuator performance, which make them difficult to execute successfully. Narukawa et al. [21] added a spring in parallel with the actuator on the hip that successfully reduced the torque cost of the actuator, but still left the disadvantages introduced by the real-time feedback control and the unnatural torso posture that leans noticeably forward during walking unsolved. La Hera et al. [24] devised a systematic trajectory planning procedure for realizing stable level-ground walking of a planar bipedal walker with a torso supported by springs, which is actuated in between the legs. The periodic motion was implemented by a complicated nonlinear exponentially orbitally stabilizing feedback controller with time-invariant gain, and the torso inclination during walking is significant and unnatural as well.

Hip SEA provides new and easier ways to achieve natural and efficient walking on level ground. During human walking, the muscles drive the leg only when appropriate, and most free leg swing is driven by gravity [25–27]. In previous studies of walking robot, it has been discovered that the actuation does not need to work throughout the walking process, and that efficient and natural motion can be generated by only applying actuation at a few key instants while the rest of the walking process remains passive. Pratt et al. [12,28], Wisse et al. [29,30], Raibert et al. [31–33] and the author's colleagues [34–36] have all verified this principle in their walking or hopping robots such that complicated motion can be implemented by a simple event-based state machine. Events, i.e., the switch condition of the state machine, can be triggered by the system state or the system clock, which can be very flexible in its selection. In this study, the events are chosen from those that can be easily obtained in the system, such as detecting the landing impact of the swing leg by a switch under the feet and timing the actuation duration via the system clock.

Considering the concrete approaches to realizing level-ground walking based on the passive dynamics of the bipedal robot, some previous researchers have introduced actuations and controls to replace the slope to supply energy to the system [29,30,37–41]. Such methods effectively use the dynamics of the robot, resulting in an efficient and natural gait. Because of the similarity between elastic potential energy and gravitational potential energy, springs in the SEAs can be used as a medium to store and control energy to achieve stable walking on level ground.

A bipedal walking robot is a typical hybrid nonlinear system. Since the bifurcation and chaos phenomena in passive dynamic walking models were first reported by Goswami et al. [42] in 1996, they have attracted the continuous attention of scientists in various fields. In 2014, Iqbal et al. [43] reviewed more than 100 papers on bifurcation and chaos in passive dynamic walking and its control issues. Among them, there are two results closely related to our study: Chyou et al. [4] discovered that period-doubling bifurcation gait appeared in the compass-like model with a torso supported by hip springs with increasing slope angle; and Farshimi et al. [6] found that there were various routes to chaos in the simplest walking model with a torso supported by hip springs, and the growth of the mass ratio of the torso to the hip would cause quasi-period bifurcation, namely Neimark–Sacker bifurcation. In our model, not only the torso and the springs, but the actuation and control via the hip SEAs are involved, therefore, we have more means to take advantage of the unique characteristics of this nonlinear system. The main advantage of the proposed actuated system is that its control parameters are time durations and angular position, which are easy to be controlled in practice.

As in a normal nonlinear dynamic system, there is an unstable period-1 gait embedded in the bifurcation gait. Comparing this with the bifurcation gait, the latter has more diverse walking patterns while the former has advantages in terms of energy efficiency and walking speed. Asano et al. [44,45] used a rimless wheel model to show that symmetric (period-1) gait had better energy efficiency. Harata et al. [46,47] also found that the period-1