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Unified bipedal gait for autonomous transition between walking and running in pursuit of energy minimization

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HIGHLIGHTS

- Unified controller for bipedal walking and running is proposed.
- D-SLIP model can switch gait between walking and running by damping ratio.
- Virtual constraint is derived from D-SLIP dynamics to represent both walking and running.
- Damping ratio is designed to be switched at the timing to minimize energy consumption.
- Energy consumption has been mostly minimized in 55 successful simulations.

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ABSTRACT

This paper addresses "unified bipedal gait" control, which autonomously selects the energy-minimized gait from walking and running at any feasible gait speeds. Humans select walking/running at low/high speed in pursuit of energy minimization and transition between them naturally. Despite the quite different behaviors of walking and running, human gaits share an inherent controller. The unified bipedal gait uses the inherent controller, which implements passive dynamic autonomous control (PDAC) based on a damping and spring-loaded inverted pendulum (D-SLIP) model. Although this D-SLIP could cause chaotic motions, compliance in the D-SLIP dynamics switches behaviors between walking and running, that is, low/high compliant legs for walking/running. This property is employed by the virtual holonomic constraint of the PDAC to extract the required characteristics of walking/running from the D-SLIP dynamics while restraining the chaotic motions for asymptotic stability. As a result, the unified bipedal gait bifurcates to walking and running via autonomous transition to minimize energy cost at any feasible gait speeds.

1. Introduction

A bipedal gait is classified into walking and running according to the flight phase. In principle, walking is switched to running whenever the gait speed is over a boundary speed (nominally when the Froude number is equal to 1) because the support leg is forced to leave the ground. Humans, however, switch the gait between walking and running at about 0.5 under any gravity [1], and naturally select a low/high gait speed to minimize energy consumption. Note that this value, 0.5, is calculated by the square of the Froude number in this literature, that is, it can be converted into about 0.7 according to the definition of the Froude number.

In humans, the transition between walking and running appears to be seamless and unobstructed, despite the quite different behaviors of these gaits. We hypothesize that walking and running controllers have an inherently unified mechanism that facilitates the natural transition in accordance with internal states. The first piece of evidence for our hypothesis is given by this transition, which shows an intermediate gait. The intermediate gait with the characteristics of both walking and running has been confirmed by analyses to optimize the energy minimization [2,3].

In mathematical analyses, human walking and running are regarded as two separate models based on their characteristics. Walking is modeled by an inverted pendulum model (IPM) with

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straight legs [4–6], and running is modeled by a spring-loaded inverted pendulum (SLIP) model with compliant legs [7–10]. The second piece of evidence for our hypothesis is given from these two models. Both models commonly use a point mass on the center of gravity (COG) connected with a pendulum, and they are different only in terms of compliance of the legs.

From the above two pieces of evidence, we expect that a human achieves walking and running by one inherent controller. The design of the inherent controller is based on a single model that can adjust its internal compliance. Although we could assume that two controllers are used simultaneously, interference between the two would produce undesirable negative effects.

Humanoid robots with multiple degrees of freedom (DOFs) are expected to achieve multiple forms of locomotion, including walking and running [11–13]. To restrain chaotic motions caused by multiple DOFs, simple models as well as analytical models of human gait are generally used to achieve a low-dimensional space. Through independent analytical models such as the IPM and the SLIP models for human gait, humanoid robots have realized walking and running. Accordingly, the transition motions between these independent models must be further designed to connect them while ensuring asymptotic stability.

If the inherent controller of a human is known, the transition motion can be easily achieved by changing the internal parameters of the controller. Previous studies on the inherent controller have extended the model of walking/running to another gait (details are explained in Section 2): a gait based on the zero-moment point (ZMP) for walking to running [14,15] and SLIP for running to walking [7,16]. These extensions, unfortunately, cannot exhibit the maximal performance of the (ZMP)-based/SLIP-based gait because the characteristics of this gait cannot be adequately expressed. On the other hand, studies on a central pattern generator (CPG) [17,18] have succeeded in the transition motion between bipedal walking and running (and different gaits of quadruped) by changing the internal parameters of its neural oscillators. They, however, focuses on the brain model for locomotion and ignores the dynamics of locomotion except its periodicity.

Hence, we propose a novel "unified bipedal gait", which includes walking, running, and the transition between them, to sufficiently express the characteristics of both walking and running. The unified bipedal gait is defined as the gait achieved by the inherent controller and model unifying both walking and running, which can easily be switched according to the internal parameters (damping ratio in this research). The inherent controller minimizes the energy cost at any feasible gait speeds by transition between walking and running.

A key idea to achieve this proposal is the damping and SLIP (D-SLIP) model. The D-SLIP model expresses the IPM for walking and the SLIP model for running by low and high compliance, respectively. Compliance in the D-SLIP model is regarded as an internal parameter for the transition between walking and running. If the compliance is adjusted to minimize energy consumption, the unified bipedal gait is achieved. The controller design based on this D-SLIP is the inherent controller.

However, it is difficult to analytically derive the behavior of the D-SLIP dynamics, as reported in [19,9,10]. This is because of its nonholonomic system and the large natural manifold of the states (i.e., frequent chaotic motions).

The dynamics of the D-SLIP can be constrained and its control facilitated by passive dynamic autonomous control (PDAC) [6] is employed as the inherent controller, as shown in Fig. 1. The PDAC restrains the robot's dynamics by a virtual holonomic constraint (VHC), which restrains whole body motion as a function of the contact angle θ between the robot and the ground [20]. The VHC, which is a geometric constraint in humanoids, reduces the natural manifold of the states into the manifold of lower dimension. Hence, the VHC should be designed to extract the D-SLIP characteristics.

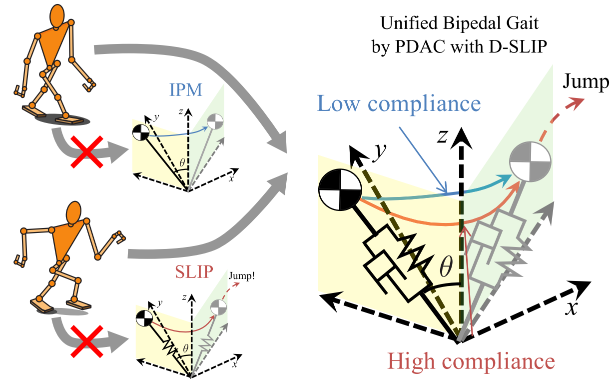

Fig. 1. Concept of the unified bipedal gait: the D-SLIP model is employed as the unified model since it can exhibit the characteristics of walking/running by changing the compliance, and the PDAC controls the D-SLIP while ensuring asymptotic stability.

Our first contribution in this paper is to propose a novel VHC design based on D-SLIP dynamics. The temporal differential equation of its dynamics is converted into the solvable spatial differential equation for the contact angle. The D-SLIP-based VHC yields the inherent controller with the internal parameter, i.e., D-SLIP compliance, to transition between walking and running. The proper manifold for the unified bipedal gait can be achieved by this controller, and the manifold should depict either walking or running unless its form is adjusted.

To obtain adjustability of the manifold as our second contribution, the D-SLIP-based VHC is successively adjusted to minimize energy consumption and to stabilize locomotion. The compliance of the D-SLIP is adjusted to promote the transition between walking and running depending on the gait speed. The achieved gait is secured by adjusting the oscillation period of the D-SLIP to be consistent with a gait step period. These D-SLIP parameters are appropriately reflected in the VHC by solving the optimization problem with constraints.

As the result, the humanoid robot achieves the unified bipedal gait by autonomously transitioning between walking and running at an intersection where their energy consumptions are reversed. Such a transition brings out superior energy consumption at any feasible gait speeds. The limit cycle at the transition is located between the limit cycles of walking and running; namely, the transition between them is stably achieved by attracting the state to another attractor. A demonstration to verify the unified bipedal gait was conducted in this study. In an open space, fast running was selected, and in a narrow space, secure walking was selected.

2. Related work on unification of bipedal gaits

The related work described below is summarized in Table 1, which categorizes the work according to the types of methods proposed for the unified bipedal gait.

2.1. ZMP-based gait

Perhaps the most well-known approach that achieves both walking and running is ZMP-based control [11,14,15] with a linear IPM or a cart-table model. This approach was originally developed for bipedal walking. However, it produces inefficient locomotion because it controls the COG according to the mechanical stability represented by the ZMP instead of the natural dynamics of a robot. In addition, the COG is highly constrained to keep height constant, and therefore, hopping and running with vertical motion are undesirable motions for this approach.