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Toward a human-like biped robot with compliant legs

Fumiya Iida [a,b,c,*], Yohei Minekawa [a], Jürgen Rummel [a], André Seyfarth [a]

[a] Locomotion Laboratory, Institute of Sport Science, University of Jena, Germany
[b] Computer Science and Artificial Intelligence Laboratory, Massachusetts Institute of Technology, USA
[c] Artificial Intelligence Laboratory, Department of Informatics, University of Zurich, Switzerland

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ABSTRACT

Conventional models of bipedal walking generally assume rigid body structures, while elastic material properties seem to play an essential role in nature. On the basis of a novel theoretical model of bipedal walking, this paper investigates a model of biped robot which makes use of minimum control and elastic passive joints inspired from the structures of biological systems. The model is evaluated in simulation and a physical robotic platform by analyzing the kinematics and ground reaction force. The experimental results show that, with a proper leg design of passive dynamics and elasticity, an attractor state of human-like walking gait patterns can be achieved through extremely simple control without sensory feedback. The detailed analysis also explains how the dynamic human-like gait can contribute to adaptive biped walking.

1. Introduction

In the fields of biomechanics and robotics, bipedal walking has been investigated for our further understanding of adaptive locomotion mechanisms of human and robots. Bipedal locomotion in artificial systems was firstly engineered by using predetermined trajectories of the leg joints. Although this approach demonstrated an outstanding versatility in locomotion behaviors, adaptivity is highly restricted because this approach requires a precise environment model and demanding computational duty for calculating the trajectories.

Research of passive dynamic walking has questioned the conventional approach. Based on biomechanical models, the so-called "compass gait model" or "ballistic walking model"[1], a number of Passive Dynamic Walkers (PDWs) have been developed and demonstrated natural walking behaviors (e.g. [2–4]). Inspired by the muscle activities in the swing leg during human walking, these models utilize no actuation and purely mechanical pendulum dynamics are used to achieve walking behavior. It has been also shown that, by implementing actuators in PDWs, dynamic walking can be achieved with high energy efficiency and little control even on the level ground [5].

More recently, a theoretical model, the so-called "spring–mass walking" has been proposed, which demonstrated walking dynamics with a considerable similarity to that of human [6]. Although the spring–mass model was originally proposed for running behavior [7–9], an extension of the original model can be applied for walking behavior, which leads to our further understanding of underlying mechanisms of human locomotion. With a few notable exceptions (e.g. [10,11]), most of the biped robots with compliant legs were developed for running and hopping behaviors in the past. Thus the nature of adaptive bipedal walking is still only partially understood.

Based on the theoretical model of bipedal walking with compliant legs, the goal of this paper is to explore a mechanically realistic model of human-like bipedal walking, which can actually be implemented in a robotic platform. In this paper, we particularly focus on the following two novel features derived from compliant legs: (a) self-stabilizing walking gait patterns with minimal motor control, and (b) joint trajectories resembling that of a human. Through the experiments in simulation and a real-world robot, we analyze how the elasticity of the leg design can be used for dynamic bipedal locomotion behavior, and compare the behavior of the system with human locomotion.

In the next section, we introduce the walking behavior of a human and the spring–mass walking model. Then we propose a new locomotion model and test it in simulation and in a robotic platform.

2. Bipedal walking with compliant legs

2.1. Analysis of human walking

In order to understand the influence of compliant legs during walking behavior, we firstly investigate the walking behavior of

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* Corresponding address: Computer Science and Artificial Intelligence Laboratory, Massachusetts Institute of Technology, 32 Vassar Street, Cambridge, MA 02139, USA. Tel.: +1 617 324 9136; fax: +1 617 253 0778.
E-mail address: iida@csail.mit.edu (F. Iida).

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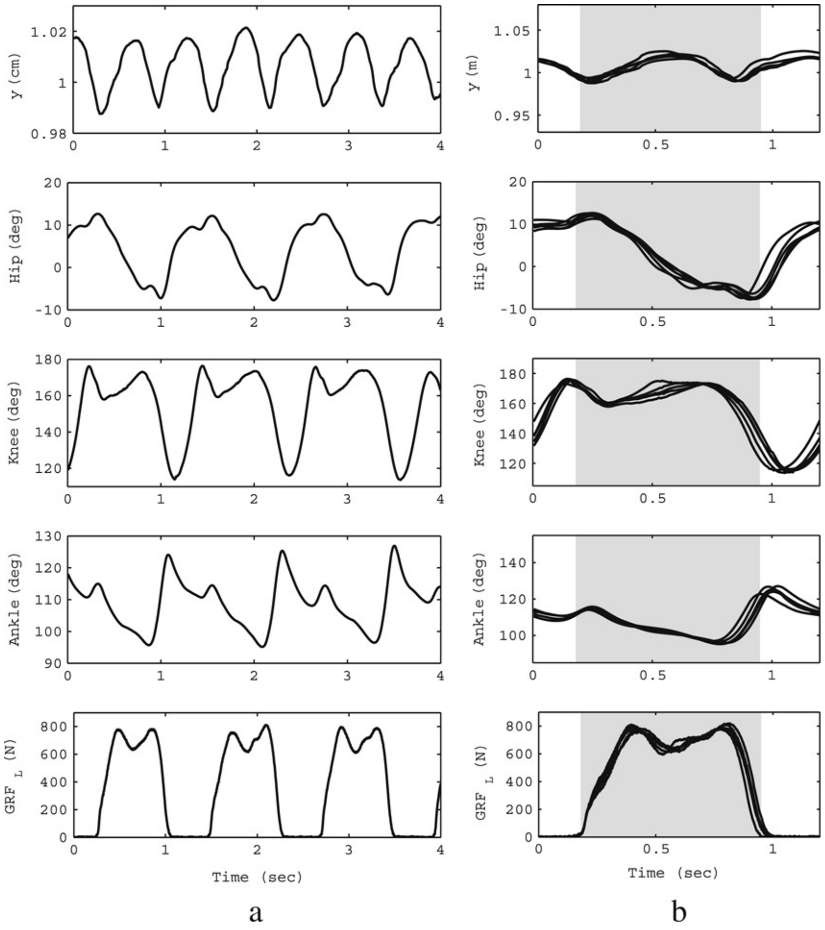

Fig. 1. Behavior of human walking. Vertical movement of the body, angular trajectories of hip, knee and ankle joints, and vertical ground reaction forces (from top to bottom figures) are shown over time-series 3 leg steps (a) and the data aligned with respect to the ground reaction force (b). Gray areas in figure (b) indicate the stance phase of the left leg.

a human subject. In this experiment, we use an instrumented treadmill with a set of high-speed infrared cameras for motion capture (6 Qualisys motion capture units; sampling frequency of 240 Hz) and force plates (Kistler 9281B11; sampling frequency of 1000 Hz), with which we analyze the kinematics of human behavior as well as the ground reaction force.

A human subject was asked to walk on a treadmill at a constant speed of 1.0 m/s for 20 s, and the kinematics and the ground reaction force were analyzed. Fig. 1 shows a set of basic characteristics of human walking, which are generally agreed in biomechanics. Firstly, walking dynamics can be clearly distinguished by observing the vertical GRF: the vertical GRF exhibits two peaks in a stance phase [12]. Secondly, the vertical body excursion during walking increases toward the middle of the stance phase, and the lowest peaks occur slightly after the touchdown and before takeoff of a leg [6,13]. And thirdly, the knee and ankle joints of the stance leg show flexion [1,14].

It is important to note that the compass gait model cannot reproduce some of these aspects of human walking dynamics (Fig. 2). Firstly, there is a significant difference in the vertical movement of the body. While the compass gait model shows the elliptic trajectory of the body movement around the foot–ground contact during a stance phase, in the human body excursion, vertical position of the body decreases at the beginning of the stance phase, then it increases and decreases; Toward the end of the stance phase, it starts increasing again. An advantage of this movement of the body could be that it has less displacement of vertical oscillation of the body.

Secondly, the behavior of the knee joint during stance phase is also different from that of the compass gait model: At the beginning of stance phase, the knee angle first decreases before a large peak. A possible advantage of the first decrease is that the knee joint could absorb the impact force at touch down. Thirdly, the ankle joint shows significant dynamics although the compass gait model has no ankle joint; There is a small peak at the beginning, and it increases toward the end of stance phase. Finally, the ground reaction force shows an M-shape, whereas the compass gait model generally shows a single peak.

In the rest of this study, we investigate a model which exhibits some of these features in human locomotion. By understanding the underlying mechanisms, we will be able to not only obtain additional insights into the nature of human locomotion, but also design and build better legged robots.

2.2. Spring–mass model for walking

The spring–mass model was originally proposed for characterizing running behavior of animals [7–9]. The model consists of a body represented as a point mass and a leg approximated by a linear spring. This extremely simple theoretical model has explained a number of eminent features of running behavior in animals including humans. Recently, this model was extended for walking behavior, which explained a few aspects of human bipedal locomotion including the complex dynamics introduced in the previous subsection [6].

Although the spring–mass model for walking shows a significant plausibility as a walking model of human, this theoretical

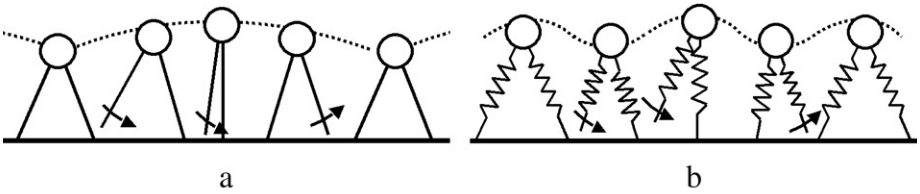

Fig. 2. (a) Compass gait model and (b) Spring–mass walking model. The dashed lines represent the vertical body excursion in these models.

model has to be elaborated for robotic implementation. In the rest of this paper, we explore a mechanically realistic model considering the theoretical spring–mass walking model and the anatomical structure of biological systems.

2.3. Model of a biped robot

Fig. 3 shows the simulation model of a biped robot investigated in this paper. This model consists of seven body segments, two motors at the hip joints with position control, four passive joints in the knee and ankle joints, and eight linear springs. The springs are implemented as substitutes for muscle-tendon systems, which constrain the passive joints. A unique feature of this robot is that six of the springs are connected over two joints, referred to as biarticular muscles in biological systems (i.e. four springs attached between the hip and the shank, two are between the thigh and the heel). For the sake of implementation in a real-world robotic platform, the dimension of this model is scaled down as shown in Table 1. There are two ground contact points in a leg defined in this model. In the simulation, we test the model in a level ground surface with a physically realistic interaction model based on a biomechanical study [15]. The vertical ground reaction forces are approximated by nonlinear spring–damper interaction, and the horizontal forces are calculated by a sliding–stiction model. It switches between sliding and stiction when the velocity of the foot becomes lower or higher than the specified limit. We used 0.55 and 0.75 for the sliding and stiction friction coefficients, respectively.

For controlling the motors, we employed a simple oscillation, because the hip joint trajectories in human walking can be roughly approximated by a sinusoid (Fig. 1). The angular position of the hip joint is, therefore, determined by the sinusoidal curve as follows:

$$P_r(t) = A\sin(2\pi\omega t) + B \tag{1}$$

$$P_l(t) = A\sin(2\pi\omega t + \pi) + B \tag{2}$$

where the three parameters are amplitude A, frequency ω and offset angle B. By using this simple control scheme, we are able to evaluate how the morphological constraints can contribute to walking behavior. This model is implemented in a planar space for the sake of simplicity, thus no rotational movement of the upper body (hip segment) is considered.

3. Experiments

3.1. Simulation result

We constructed the proposed biped robot model in the simulation environment of Mathworks Matlab 7.01 together with the SimMechanics toolbox.

We made use of the following hip joint control parameters: $A = 15$ degrees, $B = 5$ degrees, and $\omega = 2$ Hz. The hip joint control parameters were determined based on the kinematic analysis of the human experiments (Fig. 1) for the amplitude and offset angles, and we conducted systematic search of the frequency parameter with which the model exhibits a stable periodic gait as shown in Fig. 4. It is important to mention that this gait pattern is achieved without any sensory feedback: through the dynamic interactions between the ground, musculoskeletal structure, and the motor torque, the leg movement is self-organized into a stable periodic pattern.

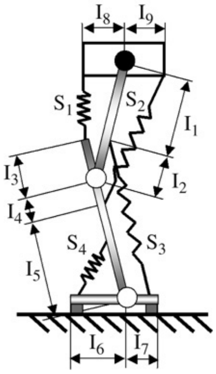

Fig. 3. Biped robot model. Only one of the two legs is shown in this figure. The model consists of a joint controlled by a motor (represented by a black circle) and three leg segments which are connected through two passive joints (white circles). Two ground contact points are defined in the foot segment.

Table 1
Specification of the robot

Param.	Description	Value
$l_1 + l_2$	Thigh	0.10 m
$l_3 + l_4 + l_5$	Shank	0.10 m
$l_6 + l_7$	Foot	0.04 m
l_2, l_3, l_4 l_7, l_8, l_9	Spring Attach.	0.02 m
S_1	Spring const.	100[a]
S_2	Spring const.	200[a]
S_3	Spring const.	800[a]
S_4	Spring const.	450[a]
M	Total mass	0.95 kg

[a] Spring constants are dimensionless.

In order to analyze more detailed behavior, the body movement, knee and ankle joint angles, and ground reaction force are analyzed as shown in Fig. 5. In this figure, for the analysis of the periodic gait, the data of 10 steps are aligned with respect to the stance phase measured by the ground reaction force. In general, the behavior of this simulated robot largely resembles that of human locomotion in terms of the salient features explained in the previous section; Vertical rise of the body starts after the leg touchdown and before the takeoff; Significant knee flexion at the beginning of stance phase; Extension of ankle joint toward the end of stance phase; Multiple peaks in the ground reaction force. The limit of this model is, however, reflected on the quantitative measures; The vertical body excursion is approximately 5% of the leg length, and the amplitude of knee flexion (i.e. the difference between the maximum and minimum knee angles) is restricted to approximately 25 degrees (they are 4% and 60 degrees in the human experiment, respectively).

The underlying dynamics of this gait pattern can be represented by observing the forces generated in the biarticular springs (Fig. 5). The dynamics of knee movement is mainly determined by the