Chapter 17
Controlled Biped Balanced Locomotion and Climbing

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Abstract This chapter describes the control principles necessary for an articulated biped model to accomplish balanced locomotion during walking and climbing. We explain the synthesizes mechanism for coordinated control of lower-body joints (i.e., ankle, hip, and knee). A humanoid biped can have a large number of degrees of freedom (DOF) that make it challenging to create physically correct, plausible and efficient motions. While we are able to define the physical principles of unintelligent models (e.g., multi-rigid body systems), the area of actively controlling a virtual character to mimic real-world creatures is an ongoing area of research. We focus on the control strategy and stability factors during continuous motion for the performing of essential rudimentary tasks (i.e., walking and climbing). We use a multi-level feedback mechanism to generated motion trajectories for the different actions, such as, stepping and walking. For example, the support leg is controlled through active forces (i.e., actuated joint feedback) based upon the control strategy to create a targeted set of parabolic trajectories for the action (e.g., stepping or climbing). The parabolic trajectories control the articulated skeleton while taking into account environmental influences (e.g., terrain height and balance information); with control parameters, such as leg-length, centre-of-mass (COM) location, and step-length being fed-back into the control mechanism.

Keywords Control • Trajectory generation • Balanced • Locomotion • Walking • Climbing • Biped • Stability • Control architecture • Jacobian

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17.1 Introduction

17.1.1 Preface

Synthesizing controlled walking and climbing biped motions is challenging and important. We study and analyse real-world human motion for popular actions, such as, walking, so that we can better understand certain principles (e.g., balance logic, stability, control reasoning, and navigation). This chapter focuses on the physical simulation of articulated character motions using a virtual environment, i.e., an interconnected set of rigid body limbs represent the biped skeleton, which are controlled through joint actuator torques. Determining what torques and when to apply them to accomplish specific motions is the challenging control tasks. We use real-world masses and dimensions (e.g., size and weight of an average human) for our model. The joint actuator torques are kept within reasonable limits during controlled motions, such as leg stepping transitions, to emulate real-world constraints. We try and make the control strategies as straightforward and graceful as possible. We demonstrate the biomechanical simulation and investigation into the creation of controlled humanoid locomotion and climbing (e.g., navigating complex terrain and posture control). We present the fundamental concepts to inspire the development of better biomechanical animation systems that are controllable and self-driven.

17.1.2 Inspiration

Humans are an inspiration to us all. Humans are capable of an infinite array of motions. Even the simplest tasks, such as stepping and jumping, are difficult to synthesize. Capturing the life-like qualities while remaining physically correct is challenging and important. Over the past few decades, robotics research has introduced ever interesting and novel approaches [1–3] which have fed into other fields (e.g., graphics [4, 5] and biomechanics [6]). For example, Raibert et al. [1], developed numerous walking models (i.e., skipping and running) based on energy preserving considerations, while Kazerooni et al. [7] exploited a weight-force ration to influence the control of lower body using pneumatic actuators. While we focus on the active joint control for steering and navigating the lower body of an articulated skeleton to accomplished coordinated balanced stepping motions, there are other interesting sub-fields that explore related areas, such as the inverted pendulum model and its numerous flavours (e.g., spring loaded inverted pendulum) for creating responsive stepping data (i.e., location of the centre-of-mass (COM) and pin-point foot location) [8, 9]. We must be reminded, as Ryave and Schenkein explains [10], that we take walking for granted, forgetting the navigational challenges involved in traversing complex terrain, such as steps, whilst avoiding collisions with objects and keeping a controlled pace.

17.2 Overview

17.2.1 Lower Body

Each leg is represented by four limbs (i.e., pelvis, foot, lower-leg, and upper-leg) and is controlled by local actuators as shown in Fig. 17.1. We model the degrees of freedom (DOF) based upon human anatomy (e.g., the knee has one degree of freedom) giving five DOF in total for each leg (i.e., ankles and hips have 2-DOF while the knees have 1-DOF). The low-dimensional skeleton has a reduced number of DOF to simplify the problem ambiguity while allowing enough flexibility to navigate complex terrain (e.g., see Fig. 17.2).

17.2.2 Joint Torques

The joint torque actuation is derived based on a Jacobian transpose methodology (i.e., virtual work displacement [11, 12]). Whereby, we analyse the current model's parameters (e.g., foot position, COM, momentum, and desired target) to create specific motion trajectories to feed into the joint controller to produce the necessary

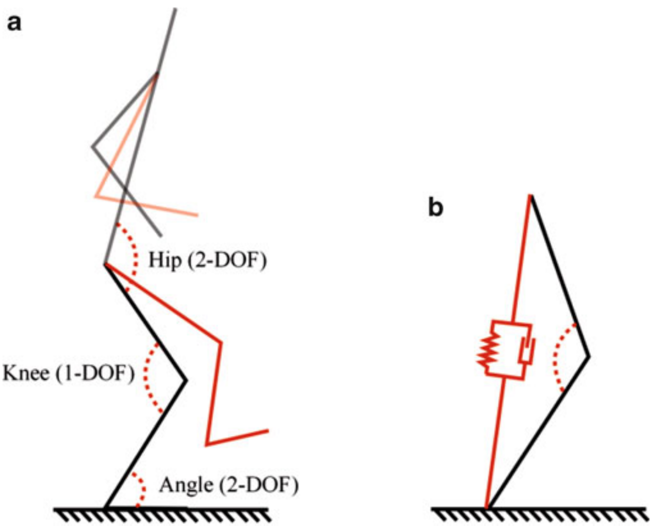

Fig. 17.1 Lower body structure—(**a**) general interconnected rigid body model for an articulated biped stepping controller; (**b**) hip and the centre-of-pressure form a low-dimensional model composed of the ground contact point and pelvis. The hip and ground contact point form a spring-damper analogy (i.e., force between the hip and ground can be converted to a torque for the knee joint)

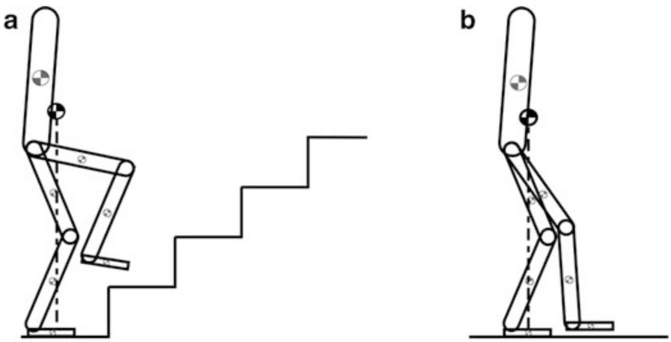

Fig. 17.2 Statically balanced stepping—(**a**) climbing a set of steps, and (**b**) walking on flat terrain. The mass of the individual limbs sum up to provide the overall centre-of-mass, which is essential for statically balanced stepping transitions

control torques. For example, the ankle and hip joints have the ability to steer, while the knee joint is limited to a single DOF (i.e., height control). We are able to produce both roll and pitch motions with the hip and ankle joint. In particular, the combined joints are highly coupled and need to work in unison to actuate the articulated model to perform directed effortless motions. This will be explained in detail in later sections as we expand upon the kinematic details of the model.

17.2.3 Balance

For models with telescopic-legs and pin-point feet (i.e., feet with no support area), the model must constantly keep stepping to remain upright and balanced. However, we focus on a model with feet, which provide a support area to create controlled statically balanced motions. Whereby, as long as the overall COM remains above the support region the biped does not need to worry about falling over. We maintain balance by manipulating the ground reaction forces (GRFs) (i.e., manipulating the centre-of-pressure COP) of the stance foot (or feet) during stepping transitions to achieve stable, controlled locomotion. While we focus on statically balanced motions (i.e., movements with low momentum where the overall COM remains above the support region), it should be noted that if we shift the centre-of-pressure around the support area (i.e., foot or feet), we can alter the body's momentum (e.g., moving the centre-of-pressure towards the toes will reduce forward body momentum while shifting it towards the back of the foot helps accelerate the body).

Clarification: keeping the overall mechanism's COM above the support region does not guarantee the stability for dynamic situations—e.g., acceleration and deceleration of the overall mass causes momentum, which would cause instability issues, such as unbalancing the mechanism. Hence, we must stress low momentum situations (i.e., motions with minimum amount of energy, such as, walking and *stepping). The principle gives a fundamental grounding that can be embellished with other techniques, such as the inverted pendulum, to form a computationally efficient and algorithmically uncomplicated concept.*

17.2.4 Dynamic Balance

Dynamic balancing is not required to return to a statically balanced state at any point during motion. Where “dynamic balancing” is sometimes referred to as “actively balancing”, since during “dynamic” movement the control system must constantly take actions to keep the body from falling over. In effect, dynamic balancing is achieved by shifting the body into a state of a continuous controlled fall.

17.2.5 Quasi-dynamic Balance

Quasi-dynamic control solutions, as we propose in this chapter, attempt to solve dynamic problems using static system approximations. They provide extra flexibility over basic static balancing solution with the ability to break the rule of always being continuously statically balanced. However, they can require long static periods of time to recover from balance disturbances. The solutions are not “truly” physically correct.

17.3 Static and Dynamic Walking

If the walking motion is done at slow speeds it is referred to as “static walking”, while at the speed of a typical human walk or faster it is referred to as “dynamic walking” [13] as shown in Fig. 17.3.

17.3.1 Static Walking

Static walking is known as *slow walking*. During foot support transitions the COM is always within the foot support area. That is, while the next foot is being placed at a new location the COM remains with the support foot region. Only once the new foot has been placed does the COM move towards the newly placed foot (staying within the foot support region of both feet). The dynamics of the body does not help the stability since the COM remains within the foot support area.

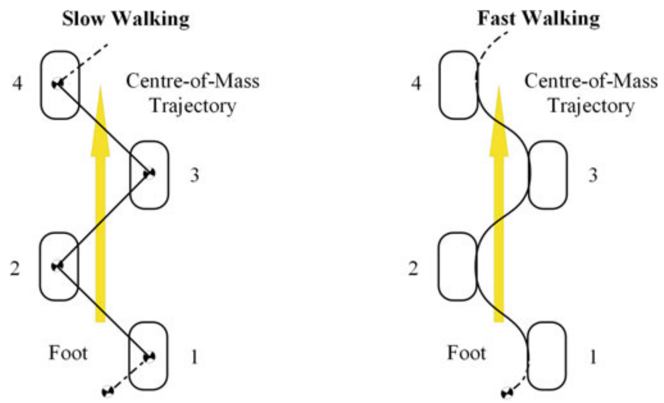

Fig. 17.3 Static and dynamic walking—during slow walking, the body's centre-of-mass (COM) always remains within the foot support area, while when the body walks at a smooth fast rate the COM is not always within the foot support area

17.3.2 Dynamics Walking

Dynamic walking is known as "fast walking". During step transitions the COM is **not** inside the foot support; however, the zero moment point (ZMP) must be inside the foot support region [14, 15].

17.4 Motion Kinematics

Environmental sensors (e.g., foot position, COM, and target direction), are used to generate joint trajectories that control the articulated model. At any moment, we can extract the character model's status, such as the current and desired joint angles. We feedback into the algorithm to derive control articulations for the desired action. A number of interesting approaches based upon this principle have already been proposed, such as Kajita et al. [16] and Muscato et al. [17]. The geometrical structure is fixed and enables us to formulate a Jacobian matrix. The Jacobian control matrix is inverted to derive control parameters.

$$\dot{x} = J\dot{q} \tag{17.1}$$

where J is the Jacobian matrix based on the link transforms, $\dot{q}$ are the joint rate of change, and $\dot{x}$ are the Cartesian links rate of change. Once the Jacobian matrix is formulated it can be inverted to feedback kinematic information [18]. Similarly, a Jacobian matrix is formulated for the knee structure.

$$\dot{q} = J^{-1}\dot{x} \tag{17.2}$$

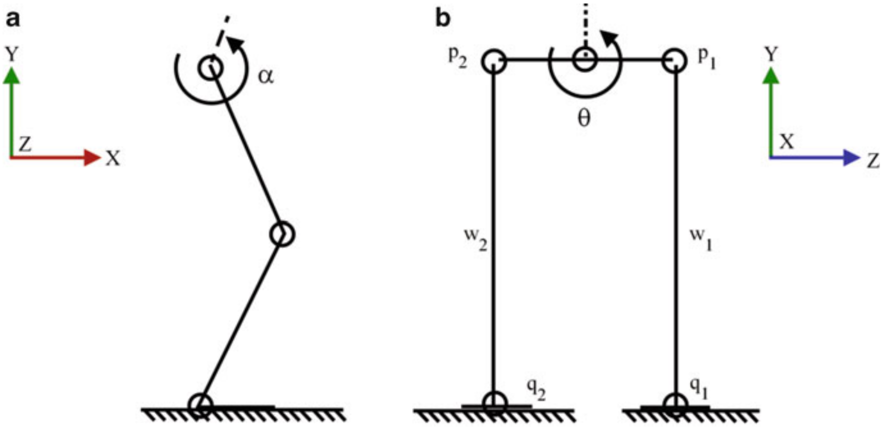

Fig. 17.4 Parameters—simplified articulated geometric lower body structure (i.e., hip and ankle) joint for deriving a set of control equations

with q representing the knee position with reference to the ankle joint shown in Fig. 17.4. The kinematic analysis leads to the derivation of the relationship between forces and joint torques that are fed to the control actuators. The virtual work principle is applied to the Jacobian transpose [11] to give the relationship between Cartesian forces and joint torques:

$$\tau = J^{\mathrm{T}} F \tag{17.3}$$

where F are the Cartesian forces in the link coordinate frame, τ are the static joint torques, and J defines the Jacobian matrix. The Jacobian matrix is calculated iteratively each frame using the current skeleton's configuration [19] (i.e., the linked manipulator formation).

17.5 Control Architecture

We explain an interconnected framework to manage the control of the biped movements at various stages (e.g., stepping transitions). We use a state machine logic to decide on the current and next state of action. A feedback loop continuously monitors the status of the model and controls the generated trajectories (e.g., interpolating end-effectors, such as the feet, between the current and target location over a specified duration). The foot transitions are defined using a set of parabolic trajectories to create arc-like swinging-leg motion and can be formulated using a

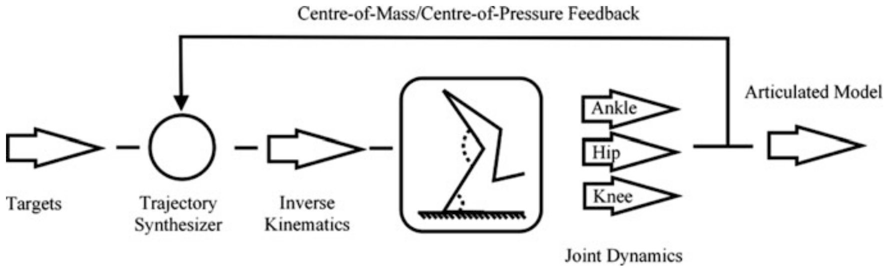

Fig. 17.5 Control framework—the interconnected framework demonstrate how the model functions to create the final motions. The trajectory information (e.g., step-height and size) are fed into the trajectory synthesizer in conjunction with feedback from the current articulated model to formulate the desired skeleton pose. The desired pose is used to calculate the necessary joint torques to feed the articulated skeleton and create the final motion

set of geometric equations [20, 21]. As shown below in Fig. 17.5, the framework is decomposed into manageable components (e.g., inverse kinematics and joint dynamics).

The low-dimensional model of the hip and ground contact point forms a fundamental underpinning of the biped stepping mechanism. The Jacobian matrix is calculated according to the posture of the biped and the centre-of-pressure position of the foot. The external virtual forces, i.e., F_{ext}, provide a feedback vector for the support leg during step transitions. The external forces are integrated into the model so that we can compensate through posture and foot reaction forces to accomplish the desired motion.

17.6 Simulation Considerations

There are a variety of open source and commercial physics-based simulation packages available for constructing articulated rigid body skeletons (e.g., collisions, revolute joints, and rigid body mechanics). A popular and well-known dynamic simulator is the Open Dynamics Engine [22, 23]. For the low-dimensional model presented in this chapter, the computational cost and memory overhead should be minimal enabling simulations to be run in virtually real-time. However, the concept is scalable and can be applied to more complex avatars with a greater number of DOF, but introduces more ambiguity, singularities, and the possibility of producing unnatural looking motions (e.g., Monty Python's famous 'ministry of silly walks' sketch).

17.7 Conclusion

This chapter explained an uncomplicated approach for creating active joint torques to synthesize autonomous lower-body motions that remain stable during continuous locomotion (e.g., compared to penalty-based methods, such as angular joint springs). The algorithm is derived and implemented without artistic intervention (e.g., emotion or style), hence the walking patterns lacked human personality. Future work would be the extrapolation of behavioural walking parameters from real-world motion capture data for injection and control into the algorithm (e.g., mixing pre-recorded trajectory motion patterns).

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