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Physics-based Animation of Full-body Human Locomotion in Altered Gravity

컴 퓨 터 공 학 과

Yun-hyeong Kim

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이화여자대학교 대학원

컴 퓨 터 공 학 과　Yun−hyeong Kim

Yun-hyeong Kim 의 석사학위 논문을 인준함

지도교수 김 영 준

심사위원 김 명 희

박 현 석

김 영 준

이화여자대학교 대학원

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Abstract

Many researchers have simulated various gravitational environments in order to understand the relationship between human locomotion and gravity. In particular, the computer-based approach measures exactly the movements at low cost and generates various movement styles. However, most of the previous work using computer-based approach is concerned with only Earth's gravity on the lower body. In this dissertation, we propose a physics-based approach to simulate the full-body animation of human locomotion in altered gravity environments. In order to develop the simulation system with a different gravity, there are several difficulties that we have to take into account: controlling high dimensional degree-of-freedoms (DoFs) of a character model, lack of motion data in various gravitational environments, and generating natural and robust human locomotion. We address these challenges and design an improved simulation system for generating human locomotion with given gravity.

As input, our method takes three captured human motions under Earth's gravitational condition such as walking, running, and turning, and sets the gravitational environments to those of the Moon, Mars, Neptune, and Jupiter. We select these environments to verify the applicability of our approach and show the differences of the synthesized motions as gravitational conditions change gradually. For a given gravity condition, we first estimate the desired velocity as well as the stride frequency of our character model using the *Froude number*, apply the altered gravity to the underlying control model. Our system generates the center of mass (COM) trajectory of a human character by using *an inverted pendulum on a cart* (IPC) control model and plans footsteps that can match the given environmental condition. In order to show that our results are visually plausible, we verify the results in three ways: we compared the simulated locomotion with an analytical gait model from the biomechanical literature and real human motion in an Apollo mission clip; we also qualitatively compared our results with others in the field of character animation. Through these comparisons, we confirm that our experimental results show plausible human gaits in different gravity with different gait characteristics.

This dissertation has the following main contributions to the state of the art. First, we propose a physics-based approach to generate natural and robust locomotion in altered gravity for a full-body human character. We deal with high DoFs of a full-body human character and our method produces realistic and robust trajectories of the body by planning the position of its four limbs

and optimize the simulated motion using desired motions based on captured motions. Second, we predict good gait properties under the altered gravity using the Froude number. We design a pre-estimation model estimating gait properties mathematically in given gravity based on an assumption of the Froude number that a gait pattern remains unchanged regardless of gravity changes. Last, we control gait properties in a direct way. It offers effective manipulation of human locomotion to keep its balance while the system synthesizes motions. To the best of our knowledge, our work is the first work that can produce the full-body simulation of a human character in altered gravity in high dimension with a diverse set of gait styles.

I. Introduction

1.1 Motivation

Manned space exploration is all humanity's dream. Such thought can be traced back to the early history of mankind. The dream finally came true in 1969 by the Apollo mission. One of the critical components in making this mission possible was to understand how human's motion can be affected and thereby adapt to a reduced gravity environment such as the Moon. This is a challenging problem, as it is necessary to generate anti-gravitational pull and apply it to a live human subject. Thus, prominent space programs such as NASA or ROSCOSMOS and biomechanical gait researchers made various attempts for altered gravity simulation using supine and erect cable suspension, parabolic aircraft flights, water immersion, and centrifugal methods [1]. Even though these physical approaches are effective and indispensable for astronauts, they can be dangerous at times, costly to build, or difficult to reproduce the results and collect their data to analyze them afterwards.

On the other hand, computer-based simulation techniques also have been employed to study human motions under reduced gravity conditions. These techniques are largely inspired by biomechanical research and are based on a simplified human model in low dimension. Even though these attempts are useful as they match the results of the physical experiments to some degree, they are still limited in terms of generating a diverse set of human gaits in a realistic setting. Moreover, lack of full-body simulation makes the results less visually appealing and is a serious limitation to be used for computer-graphic or computer-animation applications such as movie VFX, video games or virtual reality.

The ability to simulate full-body characters in computer field has a wide range of potential uses in graphical and biomechanical applications because simulated characters can adapt to changes in the environment such as gravity. Many physics-based character controllers have been presented that produce robust motion for locomotive behaviors including walking and running on flat, sloped and uneven terrains. However, earlier control techniques assume that a simulated character moves in Earth's gravity. Direct application of these techniques to a reduced-gravity environment would not work due to the following reasons. The underlying control model is designed for human locomotion in Earth's gravity. For instance, the popular inverted pendulum (IP) model used by many prior character control techniques is based on a perfect exchange of kinetic and potential energies. However, according to the biomechanics study such as [2], [3] [4], this is not true in a reduced-gravity environment, and such an effect should be taken into account for a proper simulation. Moreover, existing bipedal control techniques assume a certain pattern of footstep sequences which will determine the motion of the rest of body. Such a pattern should be modified in a different gravity environment from that of Earth [5], [6], [7].

1.2 Research Goals

Our goal is to generate a full-body animation of human locomotion including walking, running, and turning under altered gravities such as the Moon, Mars, Neptune, and Jupiter. The gravitational forces on the Moon, Mars, Neptune, and Jupiter range from about six times less to about two and a half times bigger than that on Earth.

We provide a bipedal controller, which generates different gait styles such as walking, running, and turning, and design a direct way to control gait patterns. These enable the biped to adapt to environmental change. Particularly, modifying foot patterns is a key to simulating locomotion. If a bipedal character misses the contact timing, it can easily fall down or move unstably.

We show the applicability of our method for environments with various gravities and show the validity of the resulting motions as the gravitational conditions change gradually. The simulated motions are evaluated both quantitatively and qualitatively.

1.3 Challenges

Animating character locomotion has been considered difficult to develop because of its high dimensionality. The complexity increases due to the high DoFs of a human character and kinematic and dynamic constraints. In addition, there is little information on bipedal locomotion in other environments except for Earth. We further summarize these challenges as follows:

High DoFs of a character model: Controlling high DoFs of a biped character is difficult in the field of character animation due to the high computational cost of a control method. Early controllers used finite state machines to reduce the dimension of the problem [8] [9]. Their controllers successfully plan and generate bipedal locomotion but have a limitation: their simulated result does not look natural and the character gangles like a robot. In general, the higher DoFs a bipedal character has, the more delicate or realistic the motions can become. However, to make natural and various human motions, we need high DoFs of a character model even if the problem complexity increases.

Lack of motion data under a variety of gravity: Generating a natural full-body movement needs fundamental information about human motions. However, there are very few manned explorations data available. Among manned explorations, NASA achieved only success in sending people to the Moon but did not publicly disclose human movement data except a few video clips. Thus, we have barely enough information to generate realistic bipedal movements and it is still hard to predict realistic foot patterns. The lack of movement data makes our simulated results difficult to verify.

Natural and robust human locomotion: In the study of character animation, naturalness and robustness of locomotion remain key issues. Many researchers have studied producing trajectories of a character body using physics-based control and data-driven control. In our case, we adopt physics-based control as we need to generate bipedal motion data under various gravitational values. However, it is hard to generate natural motions using the physics-based method, since the position and orientation of a character is controlled indirectly by generating torques on each joint. Moreover, physics equations of motions with complex constraints such as contact, tracking and joint constraints are required to guarantee synthesizing plausible motions, and the strict constraints hinder dealing with unexpected events.

1.4 Results and Main Contributions

In this dissertation, we propose a physics-based approach to simulate the full-body animation of human locomotion in an altered gravity environment, such as the Moon, Mars, Neptune, and Jupiter. As input, our method takes motion-captured human motions under Earth gravitational condition, including walking, running, and turning, and predict gait properties (i.e. velocity and stride frequency) under a certain gravitational condition using a pre-estimation model based on the Froude number. We map the control model to the altered gravity and plan footsteps that can match the altered gravity dynamics of the inverted pendulum model. Using our technique, we can generate natural and robust human locomotion under various gravities including different gait characteristics. We also compare these results to an analytical model using the well-known Froude number and verify that our method matches the results known in the biomechanical literature on different gravity. Moreover, we quantitatively compare the simulated motions with the astronaut locomotion captured during the Apollo mission.

The main contributions of our work are to propose a physics-based control method to animate full-body locomotion in altered gravity, find expected gait properties under the altered gravity, and control the gait patterns of a character in a direct way. We describe the main contributions as follows:

Physics-based control for full-body animation in altered gravity: Our control algorithm finds the optimal joint torques, accelerations, and contact forces through optimization for all the motion frames. The optimization step is formulated as a quadratic program (QP) and minimizes the difference between desired and actual gait properties using objective functions. Our method enables us to produce successfully the plausible and robust trajectories of the human body by using the motion data in Earth's gravity and the physics-based control.

Finding expected gait patterns: We design a pre-estimation model based on the Froude number, which estimates the changes in gait properties from those of a simulated motion on Earth. The pre-estimation model is based on an assumption that gait patterns are consistent regardless of gravitational force, and the gait patterns are expected from the simulated motions in Earth. Thus, this method allows us to synthesize natural motions.

A direct way to control gait properties: We design our controller to produce a pendulum trajectory following the center-of-mass (COM) trajectory of a character and it is affected by the center of pressure of the feet. Controlling gait properties in a direct way is required to generate robust human locomotion under the altered gravity because the contact timing is crucial while a character moves. Our method enables us to map human poses to captured motions geometrically as well as to easily modify stride frequency and contact timing.

To the best of our knowledge, our work is the first work that can simulate the full-body simulation of a human bipedal character in altered gravity in high dimension with a diverse set of gait styles. A video accompanying this dissertation can be watched via the following link http://graphics.ewha.ac.kr/alteredgravity/.

The rest of this dissertation is organized as follows. In Chapter 2, we survey the work relevant to simulating motion in a level of gravity and an overview of our approach is given in Chapter 3. In Chapter 4, we describe how to generate human motions. First, we explain the human dynamic model and the gait patterns of it. Then, we explain online and offline optimization process in more detail in Chapter 5. In Chapter 6, we show our results and validate our methods through three ways i.e. analytical, quantitative, and qualitative comparisons. After that, we analyze our results of locomotion. At the end of this dissertation, we discuss the limitation of our approach and future work.

II. Related Work

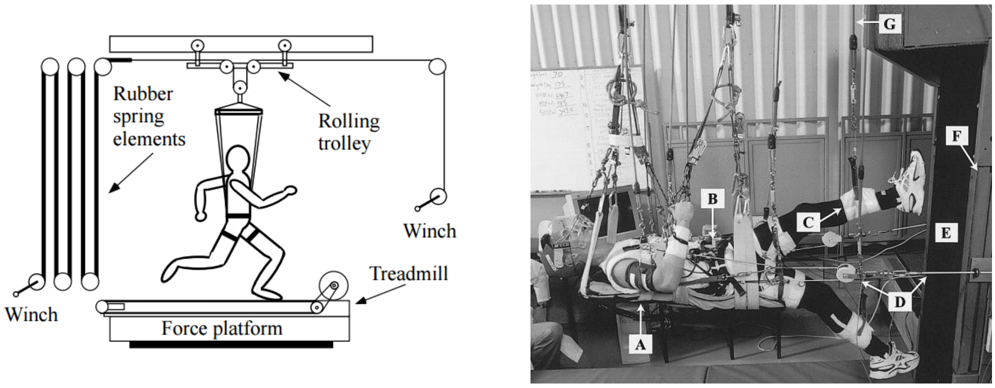
In this chapter, we survey prior work relevant to bipedal locomotion under altered gravity conditions and physics-based character control. Bipedal locomotion under altered gravity can be divided into the physical approach and computer-based approach. Both are investigated. We also study the concept of a gait pattern, which is usually mentioned in the physical approach.

2.1 Bipedal Simulation in Altered Gravity

2.1.1 Physical Approach

It is known in gait biomechanics and neurophysiology that gravity has a strong impact on terrestrial bipedal locomotion including limb oscillation rates, optimal walking speed, muscle activity patterns and gait transition speed. Thus, extensive research has been conducted in these areas in the past [10]. Many researchers have investigated the effects of gravity conditions: hypogravity and weightlessness. The purposes of this research work focus on gait rehabilitation, understanding the physiological effects of gravity, and astronaut training.

Most of existing, practical bipedal simulations in reduced gravity rely on a physical setup such as vertical or tilted body support system [7], [11], [12], [13], [14], [15]. These techniques generally include cable suspension supporting body weight either vertically or horizontally as shown in Figure 1.. These techniques have an advantage of being able to simulate reduced gravity at little cost as compared to other techniques such as parabolic aircraft flights and water immersion. On the other hand, these systems have limitations: cable suspension applies forces on parts of body and it is difficult to tune the forces to make a different gravitational environment due to rubber cables.



(a) Erect cable suspension system [15] (b) Supine cable suspension system [12]

Figure 1. Cable suspension systems for stepping on a treadmill. The systems are used to simulate a reduced gravity environment.

As research on locomotion continued, it helped to develop a new locomotion control system: a passive mechanical system for simulating a reduced gravity environment. Ma et al. proposed a new reduced gravity simulator based on a passive gravity compensation technology [13], [16]. The simulator is able to adjust the gravity force on the human body passively and provides experience in a low gravity environment for a user but their tested activities are limited only to standing, jumping and walking. Their work is also limited in terms of application due to joint friction and mass of the system (Figure2).

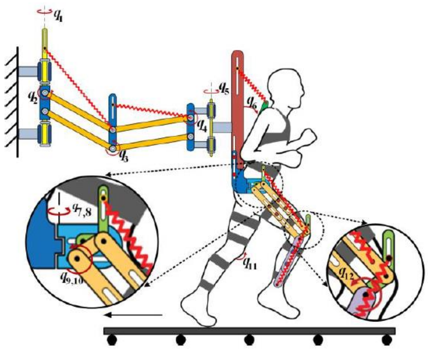


Figure 2. Passive gravity balancing system [16]

2.1.2 Computer-based Approach

There is a little research of computer-based simulation for a biped in different gravity. Ackermann and Bogert studied predictive simulation of gait at a low gravity and showed that skipping is the preferred locomotion strategy [6]. Their simulation is based on a musculoskeletal model combined with a penalty-based contact model and conducted at two movement speeds: $1.1\ \mathrm{m/s}$ and $2.0\ \mathrm{m/s}$ and three gait patterns are predicted: walking, running or skipping. They dealt with a lower body in two dimensions. Omer et al. conducted a study on humanoid walking at reduced gravity levels using a mass/spring model with ZMP-based control [18]. They design a simulation system generating foot motions for a bipedal robot, dividing walking motion behavior into sagittal and frontal planes. Because they deal with robot movements, they consider a changeable length and trunk movements that move from side to side. They show a possible approach for a bipedal robot locomotion but the robot walks only about $1.5\mathrm{m}$. In addition, it is not clear that their techniques are applicable to running or turning motions and they did not provide concrete ways of controlling a gait cycle.

2.2 Physics-based Character Control

Physics-based locomotion control has been an important problem in the field of computer graphics because of its potential to adapt to unexpected perturbations. Early controllers often used hand-designed finite state machines and feedback rules for balance control. Hodgins et al. simulated a character that runs and performs other athletic behaviors such as diving and vaulting [8]. Yin et al. introduced a balancing algorithm named SIMBICON for walking and running motions [9]. Coros et al. improved the robustness of the controller using the concept of gravity compensation [19]. Others have used the preview control of simplified dynamic models abstracting the human body for an efficient low-dimensional planning [20], [21], [22], [23]. Geijtenbeek et al. designed a muscle-based control method to simulate bipedal locomotion for various 3D creatures [17]. Based on a SIMBICON-style balance correction and an optimization strategy, the method produces stable and robust locomotion at given speeds and the amount of gravity. Recently, per-frame optimization has been used for designing controllers that improve stability and robustness. Instantaneous control signals are often obtained by formulating a quadratic programming problem, which is efficient to be solved in an online manner [20], [24],

[25], [26], [27], [28]. These approaches compute joint torques and contact forces by minimizing objective functions while satisfying the laws of physics. da Silva et al. produced a control system that combines quadratic programming with a preview control of a three-link pendulum [25]. Muico et al. simulated high-quality and agile movements such as sharp turns, [29], [30]. de Lasa et al. introduced a controller based on high-level features such as the center of mass and angular momentum [20]. Mordatch et al. improved the robustness of the controller using a spring-loaded inverted pendulum (SLIP) model [31]. Ye and Liu proposed an optimal feedback controller that helps improve the capability of one single motion capture sequence for challenging behaviors such as a walk with long steps [22]. Existing control algorithms can be further improved using controller optimization techniques. Some researchers optimized the parameters of a baseline controller to improve motion quality and robustness to unexpected disturbances or changes of terrains [27], [32], [33]. Others optimized reference trajectories to solve locomotion control problems [34], [35]. Often, reference tracking controllers used motion capture data because of its advantage for reproducing believable human motion [21], [25], [29], [34], [36], [37]. Such data-driven approaches have demonstrated that subtle details and nuances in original human motions can be reproduced. However, the issue is how to generalize an existing motion to a highly different situation. For instance, in different gravity other than 1g, has not been fully explored.

2.3. The Froude Number

In the study of the mechanics of legged locomotion, a gait pattern is described using the Froude number based on an IP model. The Froude number was proposed by D'Arcy Wentworth Thompson [38] and popularized by R. McN. Alexander [39]. They explain gait patterns through the relationship between the centripetal force and the gravitational force. To be specific, the centripetal force pivoting around the ankle joint is generated and the angular velocity occurs when he or she moves (Figure 3).

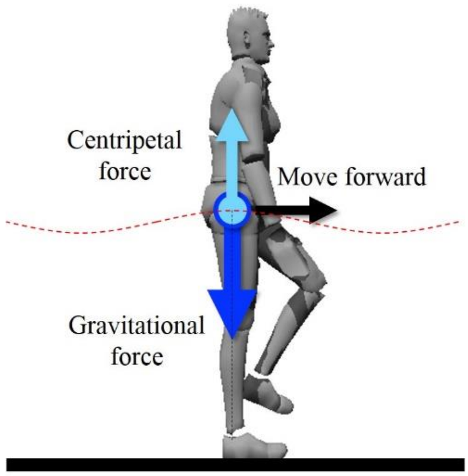


Figure 3. The centripetal force and gravitational force occur when a biped walks. The red dot line is a center of mass trajectory.

The Froude number is a dimensionless parameter of the ratio between the centripetal force and the gravitational force for a legged creature. Thompson and Alexander mathematically defined the Froude number as:

$$F_r = \frac{mv^2/h}{mg} = \frac{v^2}{gh} = \frac{s^2 f^2}{gh}, \tag{1}$$

where m is the mass, h is the characteristic length, approximated by the leg length, s is the stride length, g is the gravitational acceleration, v is the mean COM forward velocity, and f is the stride frequency, which is the number of strides in unit time. Two factors governing the forward speed v are stride length s and stride frequency f:

$$v = sf. \tag{2}$$

In other words, the forward speed can be increased either by moving legs faster or by traveling farther with each step. The Froude number is always in the range of zero and one. If the Froude number is greater than one, which means that the centripetal force is greater than the gravitational force, the biped should float in the air. According to the empirical research by [40],

[41], [42], [43], a biped switches from walking to running at $F_r = 0.5$, and the biped walks stably at $F_r = 0.25$ (Figure 4). Based on these findings, we predict the biped movements caused by a level of gravity and design a method for generating natural motions.

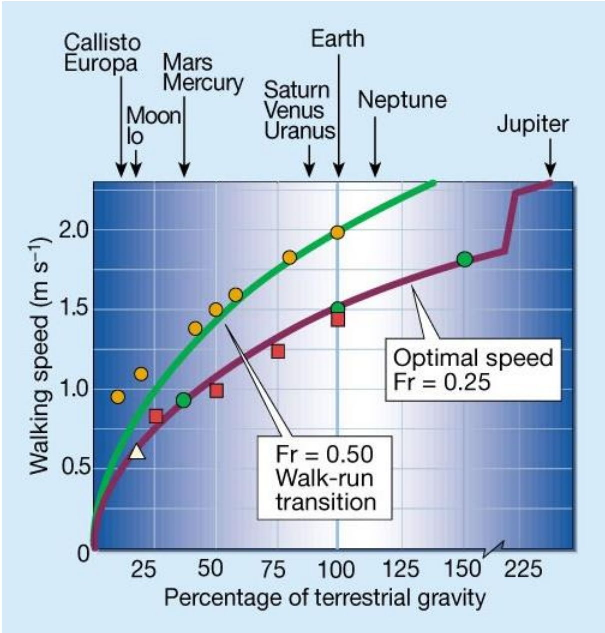


Figure 4. The curves show the relationship between walking speed and gravity [44].

III. System Overview

Our bipedal simulation is based on an IPC model that estimates the current state of motion, predicts a short future horizon of the next motion, and maintains the balance of a character. Additionally, our pre-estimation model predicts motion patterns in a given environment for our simulation system.

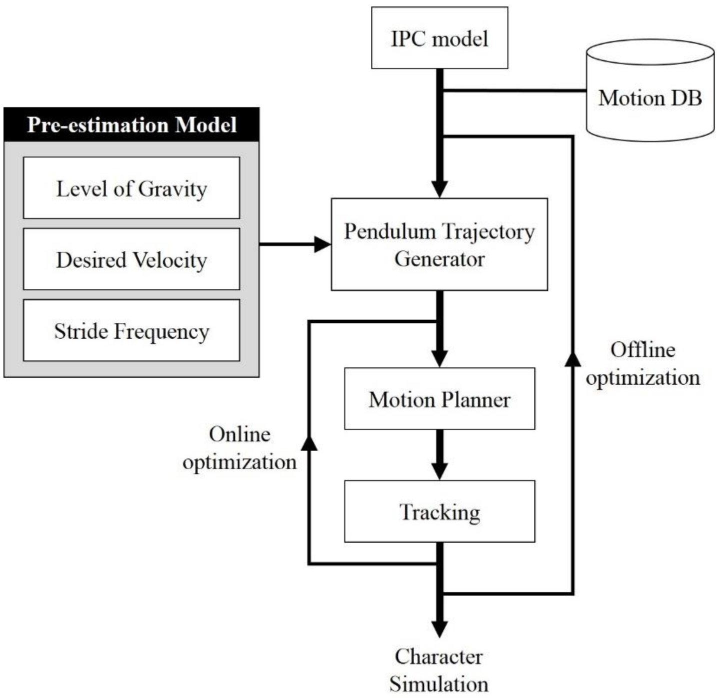


Figure 5. System diagram

As shown in Figure 5, our approach consists of four main steps: pre-estimation model, pendulum trajectory generator, motion planner, and tracking. As input, our system takes a level of gravity as well as a set of motion data captured in Earth's gravity including walking, running, and turning. Each frame of the motion data also embeds velocity and acceleration information and it is converted to a point cloud by attaching markers to the joints of the human skeletal model. The captured motions are segmented for every contact state and each motion type is annotated with a state machine; for instance, the walking and turning motions have four states and the running motion has two states. Captured motions are used to produce the COM trajectory for IP model and to improve the character locomotion by comparing the simulated motions with desired motions that are similar to captured motions.

The pre-estimation model predicts the desired COM velocity and stride frequency of the target character in altered gravity using the Froude number. From the predictive motion, we test if the motion is stable and looks natural. If so, we gradually increase the forward COM velocity and modify the stride frequency accordingly as long as the character moves stably.

Our controller is based on Kwon and Hodgins' work [21]. At every simulation time step, the pendulum trajectory generator first estimates the state of the IPC model by aligning a captured pose to the current pose of the simulated astronaut and the generator produces a trajectory for the IPC model. Then, a short future horizon of the pendulum trajectory is planned based on the current estimate of the pendulum state and using the desired velocity determined by our pre-estimation model. After planning the pendulum trajectory, the motion planner converts the trajectory into a desired trajectory of the character motion that includes footstep locations using an inverse kinematics solver. The dynamic motion is synthesized by tracking the desired motion in an online manner. Thus, full-body human motions are generated and adapted to the surrounding environment. To reproduce a more stable and natural motion, an offline optimization process is executed to find optimal end-effector positions.

In the following chapter, we further explain how to generate motions under the altered gravity and how to improve the simulated motion using optimization process. The key point in our work is to understand the relationship between gait properties and a level of gravity. Therefore, we study the Froude number, which represents the relationship between the centripetal force and the gravitational force, and a pre-estimation model to produce full-body motions under diverse gravities. Then, we explain online and offline processes that allow the control system to make natural and balanced motions.

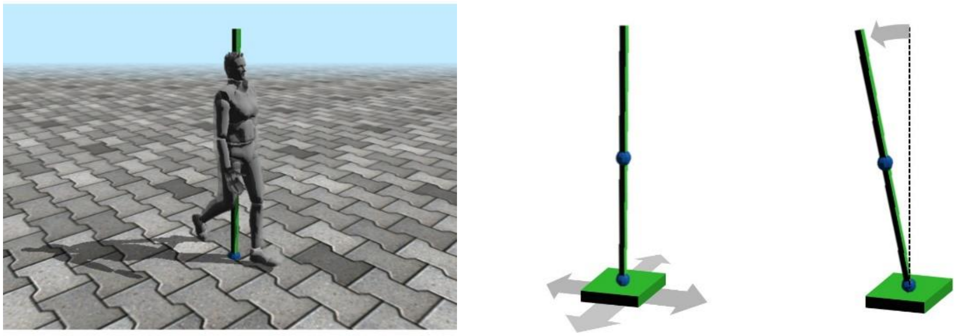
IV. Motion Generation

In this chapter, we describe effects of altered gravity on human motions and an efficient method of generating stable motions that can be well adapted to an environment with diverse, gravitational conditions. The key to generating adaptive motions is to find optimal gait properties under different gravitational conditions. We begin this chapter by describing the human character model and its gait patterns, and then explain the relationship between gravity and bipedal movement.

4.1. Human Dynamic Model

A human body has 244 DoFs [45] but all the DoFs are not utilized in the field of physics-based character control in general. Instead, researchers generally use the IPC model, which is a simplified model of the character body to generate its trajectory.

Our control system is also based on an IPC model. The pendulum model has a center of mass on the middle of the pendulum, which is located in the pelvis of a body model, for a human locomotion. The IPC model is used to analyze the captured motion data, estimate the state of motions, maintain balance and generate the simulated motion. We use two types of inverted pendulum model in our simulation method (Figure 6); they are an inverted pendulum on a cart (IPC) model and a pivoted inverted pendulum (PIP) model [21]. The IPC model is used to control stepping motions and the PIP model is used to balance itself when the character stands. The human character can move by controlling two translational joints and two rotational joints of these inverted pendulum models.



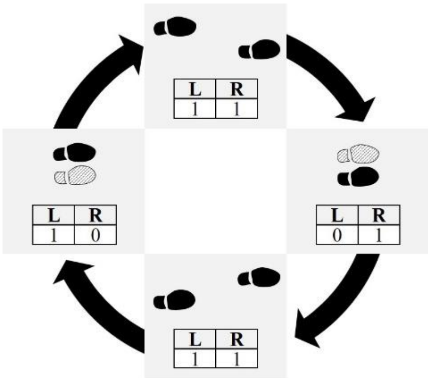
(a) human model with the pendulum (b) IPC model (c) PIP model

Figure 6. Illustrations of the human model and two types of inverted pendulum models.

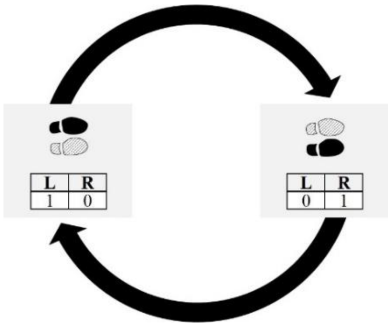
4.2. Motion States

Human locomotion is achieved by the movement of limbs and the differences of the locomotion are defined by gait patterns. We describe how to define gait patterns of the captured motions such as walking, running, and turning.

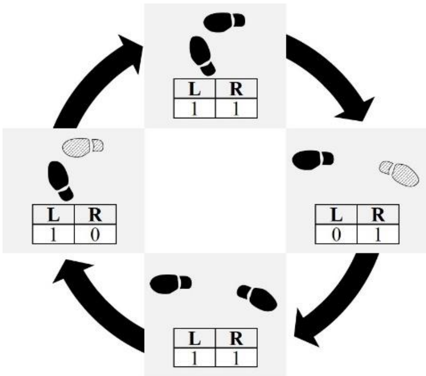
Each type of locomotion is characterized by different ways of moving arms and legs; in other words, locomotion is expressed through the movement of end-effectors. Legs have a great effect on the legged motion. We also segment captured motions of walking, running, and turning according to the changes of foot phases. In our system, there are four hip states to characterize each gait pattern: left hip swing/stance and right hip swing/stance, and motions of arms make a pair with motions of legs. Every gait pattern is described by a combination of the four states and each state is designated a weight value between zero and one. The weight value is one if an end-effector reaches the floor; it is zero, otherwise. As shown in Figure 7, the walking motion is defined using four states: left hip swing and right hip stance, left and right hip stance, left hip stance and right hip swing, and left and right hip stance; the running motion is defined using two states: left hip swing and right hip swing; the turning motion is defined using four states similar to the walking motion but the hip joint rotates when the joint is swinging.



(a) Walking



(b) Running



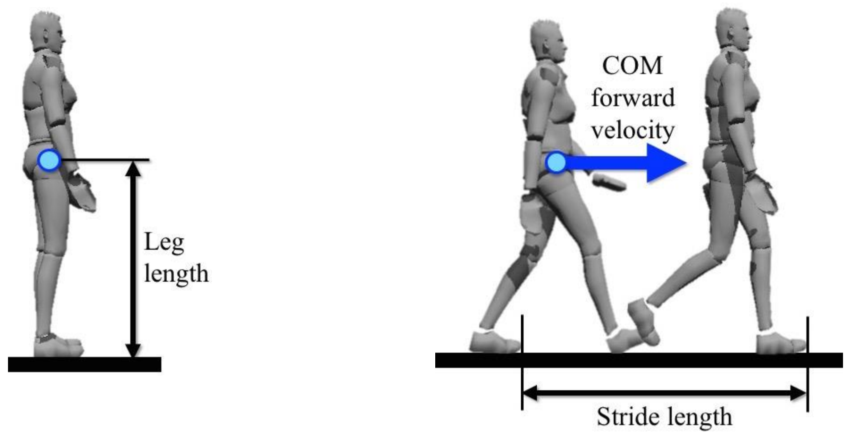
(c) Turning

Figure 7. Motion states for walking, running and turning. These gait styles are segmented at every contact state. L, R are a left foot and a right foot respectively and zero or one is a weight value for defining each state.

4.3. Pre-estimation Model

We need two steps to simulate human motions in altered gravity: setting up an altered gravity environment and designing a pre-estimation model to predict gait patterns. The changed gravity affects the human character body and forms a desired trajectory which is changed from the trajectory in Earth's gravity. After then, we design a pre-estimation model by taking the concept of the Froude number. We already know the leg length of our bipedal character model and the gravitational acceleration that our simulated environment has. Then, it is possible to calculate the Froude number for our motion under the Earth's gravity using Equation 1. We assume that a gait pattern under Earth's gravity keeps the same even if a level of gravity is changed; that is to say, we assume that the Froude number we calculated in Earth's gravity is equal to the Froude number in altered gravity. In fact, the Froude number is a constant regardless of different gravities for simulated motions.

Our control system uses four gait variables to generate a pattern of motions. The gait pattern can be expressed by $M = \{\alpha_{\text{leg}}, \alpha_{\text{vel}}, \alpha_{\text{stfreq}}, \alpha_{\text{fpos}}\}$, where α_{leg}, α_{vel}, α_{stfreq}, and α_{fpos} are, respectively, the variables for the leg length defined by our character, the forward velocity, the stride frequency, and the foot position at each motion phase such as swing or support phase (Figure 8). The forward velocity α_{vel} can be adjusted by scaling the forward velocity of a captured motion. Also, we can adjust the gait cycle duration α_{stfreq} by altering the time scaling factor that determines the rate of the captured poses which are feed-forward. We build a pre-estimation model defined by these four gait variables and apply it to the control system, which will yield the results that are similar to the captured motions.



(a) Leg length (b) Velocity and stride

Figure 8. Illustrations of leg length, COM forward velocity and stride length

The Froude number is fixed according to the gait style of a captured motion since the Froude number is a constant regardless of the changed gravities. From Equation 1, we calculate the velocity and the stride frequency of a bipedal motion:

$$v = \sqrt{F_r g h}, \tag{3}$$

$$f = \frac{\sqrt{F_r g h}}{s}. \tag{4}$$

As we know our character's leg length h and assume that the stride length s is a constant regardless of the altered gravities to avoid excessively long or short stride, from Equation 3 and 4, we get the ratio of the velocity to the stride frequency for a given value of gravity:

$$\frac{v_A}{v_B} = \frac{f_A}{f_B} = \sqrt{\frac{g_A}{g_B}}, \tag{5}$$

where A, B can be Earth, Mars, the Moon, Neptune, and Jupiter, g_A and g_B are their gravities, v_A and v_B are the forward COM velocities on A and B, and f_A and f_B are their stride frequencies on A and B. Since we know the velocity and the stride frequency from the simulated result in Earth's gravity, we can predict the velocity and the stride frequency in altered gravity using Equation 5. The velocity we calculated is set to the desired velocity for the simulated motion that we wish to construct. The calculated stride frequency is used for determining the time warping ratio, defined as the time rate that the entire motion cycle should be completed. The velocity and the stride frequency can be further adjusted manually when a different stride length is desirable to produce visually pleasing gaits without stumbling. More generally, one can also determine the optimal velocity and stride frequency for an arbitrary gravitational environment using the Froude number.

The motion planner produces limb motions based on the current estimated state of the pendulum and modifies the limb motions to make the resulting motions stable through the online optimization, to be explained in Section 5.1, that finds optimal joint torques and contract forces. The resulting full-body controller is further improved by modifying the feet trajectories using the offline trajectory optimization, to be explained in Section 5.2, because the online optimization alone may not create natural motions. Modifying the feet trajectories creates additional contact forces that change the simulated motion. Thus, the forward velocity of the simulated motion is determined by the desired velocity input to the pendulum model as well as these additional forces.

V. Physics-based Character Control using Optimization

Our control algorithm is formulated as an online optimization problem that is solved per-frame. The goal of the online optimization is to find the optimal joint torques and contact forces to control the model. At every frame, our controller adjusts the reference motion with a balance strategy presented by Kwon and Hodgins [21]. The short future horizon of the balance-recovering desired motion is instantaneously planned based on the estimated pendulum state. The motion of the full-body model is generated using a dynamics simulation that tracks the planned desired motion in an online manner.

5.1. Online Optimization

The optimization step is formulated as a quadratic program using an objective function and a set of linear constraints and computes joint torques τ, accelerations $\ddot{\mathbf{q}}$ and contact forces $\boldsymbol{\lambda}$:

$$\min_{\tau,\ddot{\mathbf{q}},\boldsymbol{\lambda}} L_{\text{tracking}} + L_{\text{end effector}} + L_{\text{torque}} + L_{\text{contact force}}, \tag{6}$$

subject to equations of motion and contact constraints.

5.1.1. Equation of Motion

The equations of motion of the humanoid model are described as:

$$\mathbf{M}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{c}(\mathbf{q},\dot{\mathbf{q}}) = \tau + \mathbf{J}_{\mathbf{c}}^{T}\mathbf{f}_{\mathrm{c}}, \tag{7}$$

where $\mathbf{q}, \dot{\mathbf{q}},$ and $\ddot{\mathbf{q}}$ are the generalized configuration of all DoFs and its time-derivatives. We use humanoid models having 39 to 54 DoFs, and their height and mass are from 165 to 177 cm and from 62 to 77 kg, respectively. All DoFs of the models except the six DoFs at the root joint are actuated by joint torques τ. $\mathbf{M}$ is the inertia matrix, and $\mathbf{c}$ combines the centrifugal, Coriolis and gravitational forces. Contact Jacobian matrix $\mathbf{J}_{\mathrm{c}}$ maps the generalized velocity $\dot{\mathbf{q}}$ to the global velocities at the contact points. $\mathbf{f}_{\mathrm{c}}$ contains the ground contact forces, represented as a linear combination of basis vectors of Coulomb friction cones:

$$\mathbf{f}_\mathrm{c} = \mathbf{V}_\mathrm{c}\boldsymbol{\lambda}, \tag{8}$$

where $\mathbf{V}_\mathrm{c}$ contains the basis vectors for friction cones and $\boldsymbol{\lambda}$ is a coefficient vector as contact forces.

5.1.2. Contact Constraints

Contact constraints are represented using a set of linear inequality constraints:

$$\boldsymbol{\lambda} \geq \mathbf{0}, \tag{9}$$

$$\mathbf{a}_\mathrm{c} = \mathbf{V}_\mathrm{c}^T\mathbf{J}_\mathrm{c}\ddot{\mathbf{q}} + \mathbf{V}_\mathrm{c}^T\dot{\mathbf{J}}_\mathrm{c}\dot{\mathbf{q}} + \dot{\mathbf{V}}_\mathrm{c}^T\mathbf{J}_\mathrm{c}\dot{\mathbf{q}} \geq \mathbf{o}_\mathrm{c}, \tag{10}$$

where Equations 9 and 10
$\boldsymbol{\lambda} \geq \mathbf{0}$, (9) represent the friction cones and the velocity cones, respectively. $\mathbf{a}_\mathrm{c}$ denotes the global accelerations at contacts, and $\mathbf{o}_\mathrm{c}$ denotes the velocity-dependent offsets at contacts [20]. The objective function for the per-frame optimization consists of four terms. All terms are in a quadratic form with respect to optimization variables $\ddot{\mathbf{q}}, \mathbf{a}$, and $\boldsymbol{\lambda}$.

Tracking objective: The tracking objective L_tracking minimizes the difference between the desired and the actual accelerations from the captured reference motion.

$$L_\mathrm{tracking} = l_\mathrm{tr}||\ddot{\mathbf{q}}_\mathrm{d} - \ddot{\mathbf{q}}||^2, \tag{11}$$

where l_tr is the weighting factor for the tracking objective, and $\ddot{\mathbf{q}}_\mathrm{d}$ and $\ddot{\mathbf{q}}$ are the desired and the actual accelerations, respectively. We compute the desired acceleration based on the balance-recovering desired motion as follows:

$$\ddot{\mathbf{q}}_\mathrm{d} = k_p f_\mathrm{diff}(\mathbf{q}_\mathrm{r}, \mathbf{q}) + k_\mathrm{d}(\dot{\mathbf{q}}_\mathrm{r} - \dot{\mathbf{q}}) + \ddot{\mathbf{q}}_\mathrm{r}, \tag{12}$$

where $\mathbf{q}_\mathrm{r}, \dot{\mathbf{q}}_\mathrm{r},$ and $\ddot{\mathbf{q}}_\mathrm{r}$ are the desired position, velocity and acceleration of all DoFs, and k_p and k_d are the corresponding gains. The function f_diff computes the difference between two positional DoFs of the corresponding joints.

End-effector objective: The end-effector objective $L_{\mathrm{end\ \ effector}}$, tries to track the desired end-effector positions and orientations in the Cartesian space because the foot-step location is critical for balancing and the planned footsteps are satisfied accurately. End-effector objective is described as:

$$L_{\mathrm{end\ \ effector}} = l_{\mathrm{ee}} \sum_{i} \left|\left|\ddot{\boldsymbol{y}}_{\mathrm{d}}^{i} - \ddot{\boldsymbol{y}}^{i}\right|\right|^{2}, \tag{13}$$

where l_ee is the weighting factor for the end-effector objective, and $\ddot{\boldsymbol{y}}_{\mathrm{d}}^{i}$ and $\ddot{\boldsymbol{y}}^{i}$ are the desired acceleration of the i^{th} end-effector and actual acceleration of the i^{th} end-effector from the captured reference motion.

Joint torques and contact forces objective: Minimizing joint torques and contact forces are important for obtaining smooth motions by reducing the impact from the ground. These objective terms are also necessary for making the objective function positive definite:

$$L_{\mathrm{torque}} = l_{\mathrm{torq}} ||\tau||^{2}, \tag{14}$$

$$L_{\mathrm{contact\ \ force}} = l_{\mathrm{cf}} \left|\left|\boldsymbol{\lambda}\right|\right|^{2}. \tag{15}$$

The weighting factors l_torq and l_cf are empirically chosen based on the trade-off between the stability of control and the motion smoothness.

5.2. Offline Optimization

Although the initial controller works successfully after careful tuning of the weighting factors, the controller is not optimal in terms of motion quality, and cannot be generalized for environments with altered gravity. For producing controllers that work in such environments, we first modify the forward velocity of the character and the duration of a gait cycle, then employ a trajectory optimization technique proposed in [21].

5.2.1. Forward Velocity and Gait Cycle

Based on the preview control of an inverted pendulum model, the forward velocity of the full-body character can be easily adjusted by changing the desired speed of the pendulum model. Because our controller uses the stride frequency of the captured reference motion by default, decreasing the forward velocity results in proportionally decreased stride. When unnecessarily long or short stride looks unnatural, we adjust the stride frequency by time warping the captured reference motion. In our experiments, the forward velocity turns out to be a more important factor for robustness than the stride frequency. Thus, we first decide the forward velocity of the character using Froude number, and the stride frequency is chosen empirically to naturally reproduce the observed behaviors of astronauts, for instance, on the Moon.

5.2.2. Trajectory Optimization

Once the forward velocity and the stride frequency are fixed, we obtain a working controller by optimizing some of the input parameters to the initial controller. The trajectory optimization is performed in an offline preprocessing step for the first ten strides, and the resulting controller can robustly generate stable locomotion indefinitely. We optimize only the feet trajectories because the feet trajectories are the most important components for producing stable gaits. Assuming that the locomotion has symmetric gaits, the dimensionality of the search space is 18. The dimensionality corresponds to six three-dimensional control points for a foot displacement map, and the other foot uses the mirrored version of the displacement map. The same displacement map is used repetitively for all strides.

The trajectory optimization uses two objective terms to be minimized. The first term, E_{pd}, penalizes the deviation of the simulated motion from the original reference motion:

$$E_{\mathrm{pd}} = \sum_{1}^{N} d_{\mathrm{pose}}(\mathbf{q}_{\mathrm{r}}, \mathbf{q}), \tag{16}$$

where N is the number of frames and d_{pose} measures the difference between the simulated pose and the corresponding pose of the time-warped reference motion. The pose difference is measured using point cloud matching about the vertical axis, and the height difference of the COM between the simulated and captured pose is ignored. This is because the character tends to jump higher when the gravity is significantly reduced. The second term, E_{sd}, measures the similarity between strides to produce steady motion:

$$E_{\mathrm{sd}} = \sum_{i=1}^{\mathrm{numstride}-1} \sum_{j}^{N_{\mathrm{s}}} d_{\mathrm{pose}}\left(\mathbf{q}_{i,j}, \mathbf{q}_{i+1,j}\right), \tag{17}$$

where i denotes the i^{th} stride, and N_{s} represents the number of frames in a stride.

VI. Results and Discussion

In this chapter, we show three types of results from our simulated locomotion on the Moon, Mars, Earth, Neptune, and Jupiter, and show that our system generates robust and smooth trajectories for an inclined terrain with an external force perturbation. We also analyze them by making analytical, quantitative, and qualitative comparisons.

6.1. Experimental Results

We implemented our simulation system using Lua and C++ programming languages on a Mac Pro machine equipped with 3.5 GHz 6-Core Intel Xeon E5 and 16 GB memory under Mac OS X Yosemite. We used quadprog [46] and the covariance matrix adaptation evolution strategy (CMA-ES) [47] for online and offline optimization in our controller.

We use walking, running, and turning motions, captured in Earth's gravity, as reference motions for simulations. All the simulated motions show stable movements in altered gravities. The simulated full-body motion is rigged into an astronaut mesh-model and rendered with 3ds Max®.

Full-body Human Character: Our human character for simulation has from 39 DoFs to 54 DoFs (50 DoFs on average), and their heights and masses range from 165 cm to 177 cm and from 62 kg to 77kg, respectively. The characteristics of our simulation models are different depending on gait types and summarized in Table 1 including DoFs, weight, height, and leg length. As shown in Figure 9, the character has an upper body and a lower body: head, neck, spine, clavicles, arms, hands, pelvis, two legs, feet and so on. Its pelvis, where its center of mass is located, has six-DoF unactuated joints and its knees and elbows have one DoF hinge joint. The others have three-DoF joints.

Table 1. Biped models characteristics

Property	Walking	Running	Turning
DoFs	54	39	54
Weight (kg)	62	75	77
Height (m)	1.60	1.80	1.75
Leg length (m)	0.82	0.93	1.00

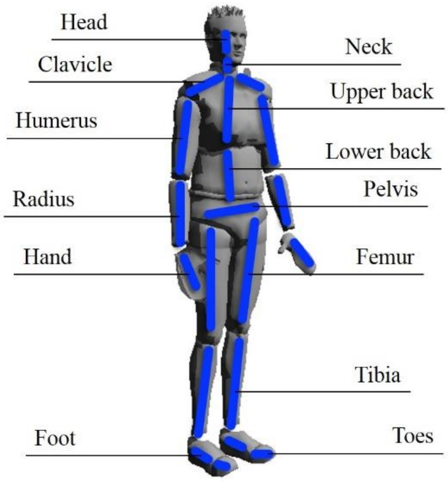


Figure 9. Human character model used in our control system

Simulated Results: Figures 8, 9, and 10 as well as the accompanying video show our simulation results including walking, running, and turning under the gravitational conditions of the Moon, Mars, Earth, Neptune, and Jupiter, respectively.

Using the reference motions, we simulate motions in Earth's gravity first. Then, we compute their average COM forward velocities. Using our pre-estimation model, we determine the desired forward velocity in different gravities. Then, we increase the COM velocity gradually starting from the desired velocity as long as the character does not lose its balance. All motions are post-optimized using objective function and a set of linear constraints in Equation 6.

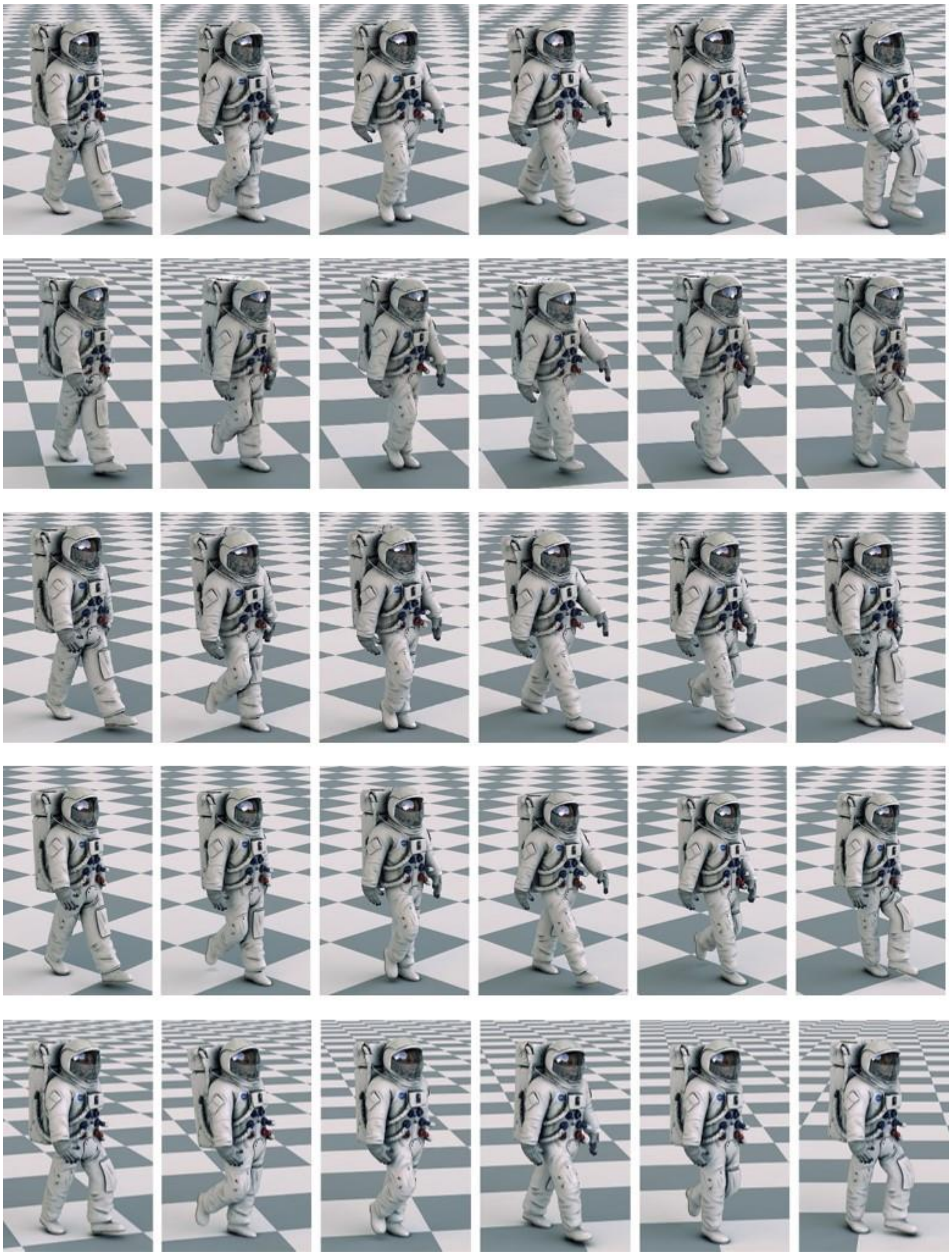


Figure 10. Simulated walking motions in the gravity of the Moon, Mars, Earth, Neptune, and Jupiter from top to bottom rows, respectively.

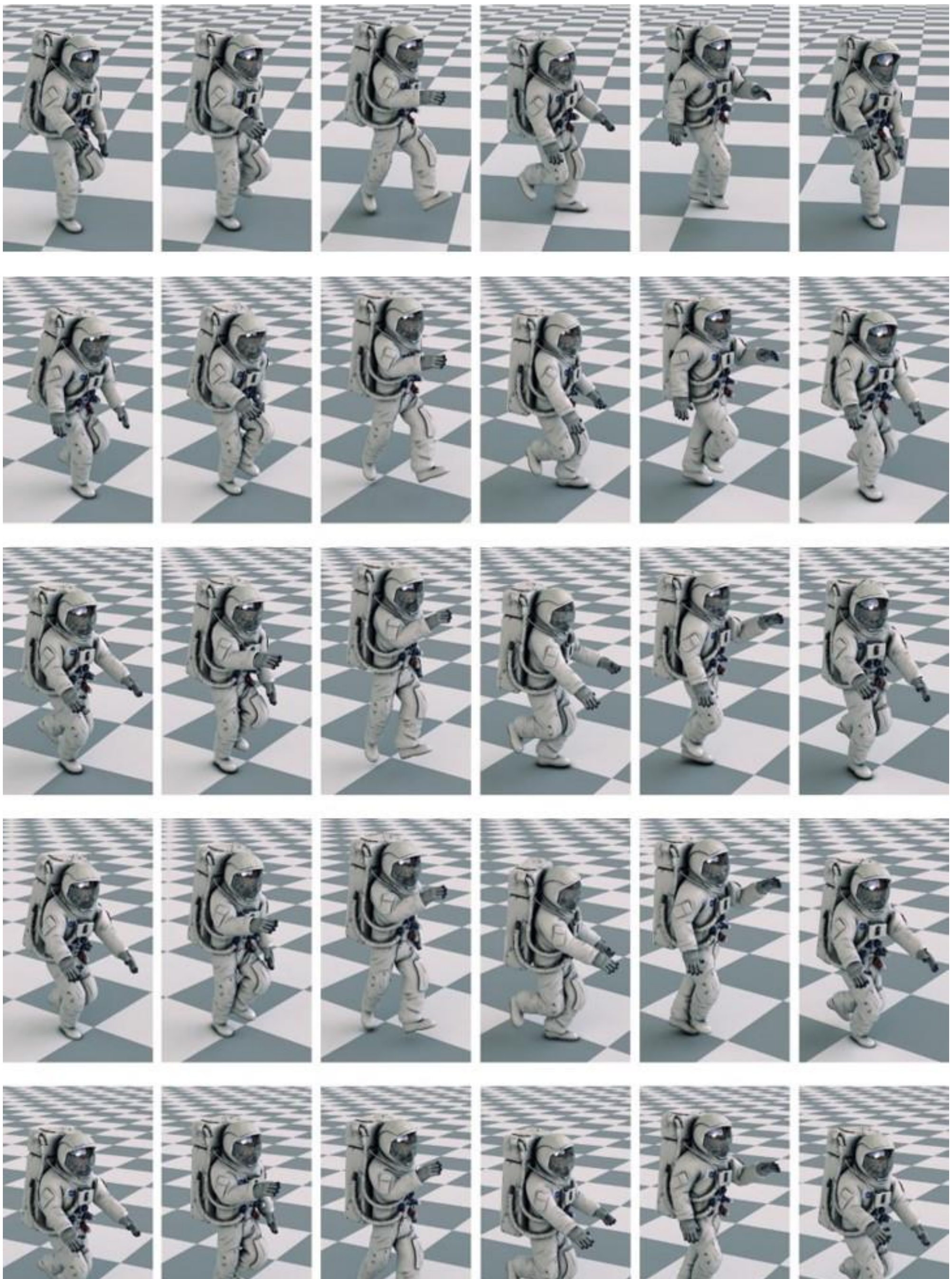


Figure 11. Simulated running motions in the gravity of the Moon, Mars, Earth, Neptune, and Jupiter from top to bottom rows, respectively.

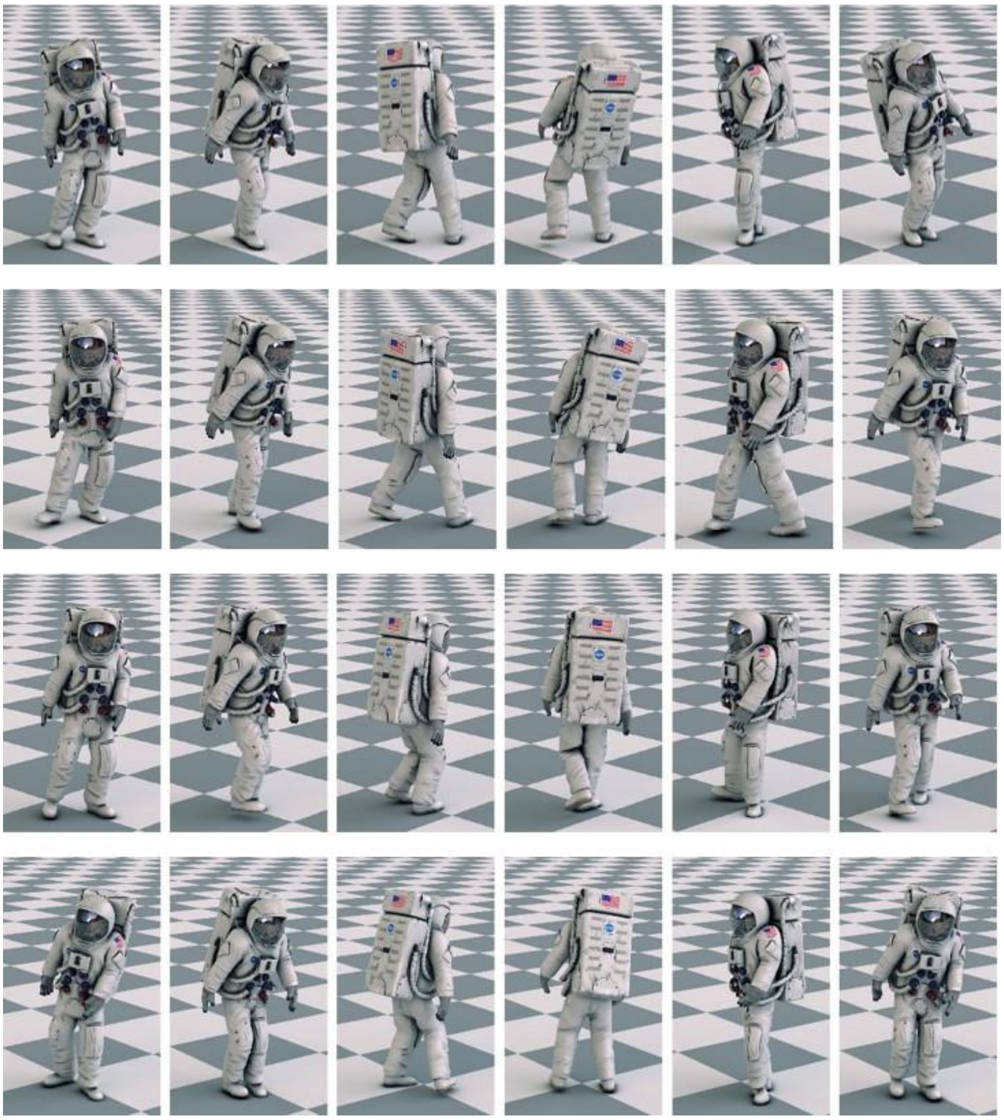
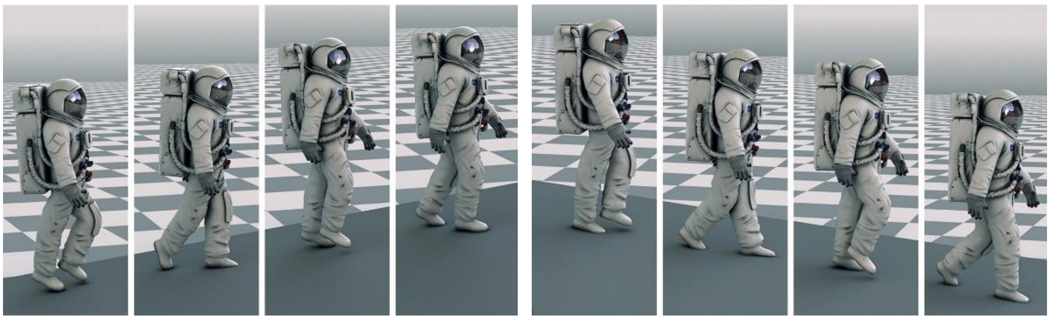


Figure 12. Simulated turning motions in the gravity of the Moon, Mars, Earth, and Neptune from top to bottom rows, respectively.

Inclined Terrain: We test the capability of our controller to move over inclined terrain in altered gravity, where the inclination angle varies between ± 5 degrees. As also shown in the accompanying video, the character walks stably without losing its balance or falling down under the Moon's gravity. For $+5$ degrees of inclination angle, the character slows down from 0.50

m/sec to 0.45 m/sec (Figure 13-(a)). For -5 degrees of inclination angle, the character speeds up from 0.50 m/s to 0.61 m/sec (Figure 13-(b)). The character can also walk well over inclined terrain in other planets: Mars, Neptune, and Jupiter.



(a) $+5$ degrees inclined terrain (b) -5 degrees inclined terrain

Figure 13. Simulated walking motion in gravity of Moon for ± 5 degrees inclined terrain

External Perturbation: We verify that our controller can recover from external perturbations. As shown in Figure 14, we demonstrate that our simulated character can walk stably in the gravity of the Moon when being pushed by unexpected external forces that are equivalent to 75.0 N for the duration of 0.2 sec. In this case, the character moves forward in balance even though the character is placed in the unexpected situation.

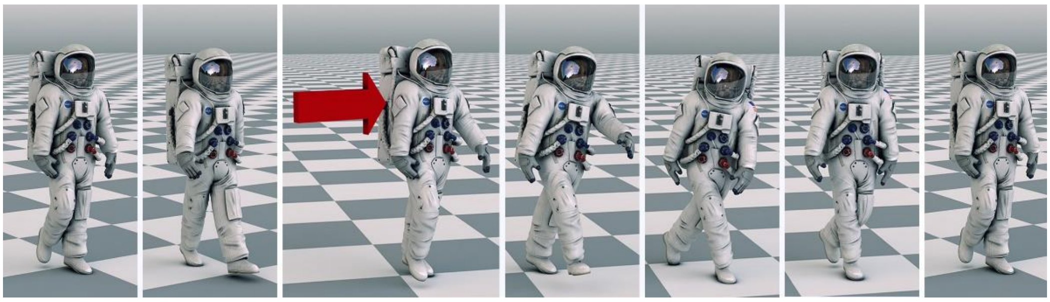


Figure 14. Simulated walking motion in the gravity of the Moon with external force perturbation, where the red arrow shows the direction of the external force with 75N for 0.2 sec.

6.2. Method Validation

We analyze the simulated results by making analytical, quantitative, and qualitative comparisons. First, we discuss the validity of our results via a mathematical model based on the Froude number. Then, we make a quantitative comparison between our result motions and the movements of astronauts in a video clip of the Apollo Mission that is provided by National Aeronautics and Space Administration (NASA). Finally, we discuss the differences between our work and other works qualitatively.

6.2.1. Analytical Comparisons

We analyze the quality of simulation based on the Froude number. Figure 15 shows graphs for the COM velocity with respect to different gravitational conditions. The used motion here is walking. The dotted line is a curve for the expected COM velocity, estimated from Froude number using Equation 3 and the blue curve is a graph of our simulated results interpolated between levels of gravity: the Moon's, Mars', Earth’s, Neptune’s, and Jupiter’s gravities. The result shows that our simulated results closely resemble the analytical one based on the Froude number except for the Jupiter case. In Jupiter case, we need to set the COM velocity intentionally low in order that the character bears the gravity force and walks. In case of running motion, we did not make a comparison, as we set the velocity as high as possible regardless of the gravitational condition so that the velocities in different gravities are uniform, which gives visually pleasing results in our experiments. In case of turning motion, an analysis using Froude number is not very meaningful, as the motion contains rapid rotations and the forward velocity is not well defined.

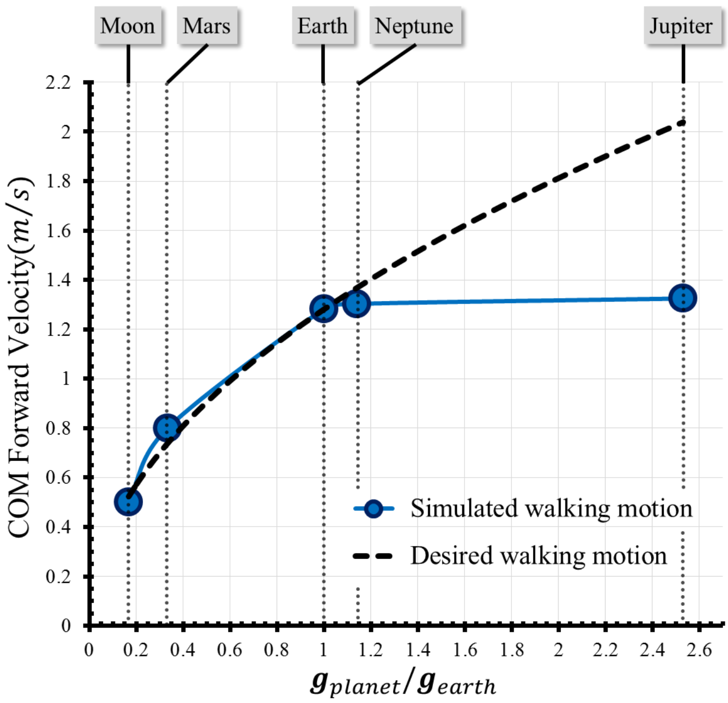


Figure 15. Comparison against an analytical model using Froude number for walking motion. The x and y axes in the graph denote the normalized gravity with respect to the Earth's gravity and the COM forward velocity, respectively. The dotted line denotes a curve that is based on the analytical model using Equation 3 and the blue line denotes a curve that is based on our simulation results. These curves show a similar pattern of results except for Jupiter.

6.2.2. Qualitative Comparisons

Geijtenbeek et al. presented a muscle-based controller for the simulated locomotion of various 3D bipedal creatures [17]. Based on an SIMBICON-style balance correction and an optimization strategy, the method produces robust locomotion at given speeds and the amount of gravity. Omer et al. conducted a study on humanoid walking at different gravity levels using a mass/spring model with ZMP-based control [18]. However, it is unclear whether these techniques are applicable to human locomotion with different gait styles including running or turning. Also, these approaches do not provide a direct way to control the stride frequency of the simulated gaits.

We build our controller based on a tracking algorithm proposed by Kwon and Hodgins [21] and employed by other researchers [37], [48]. Their controller is based on the common idea of preview control of inverted pendulum models [49], [50]. However, the inverted pendulum on a cart (IPC) controller proposed in [21] differs in that it plans a smooth pendulum trajectory that follows only the center of mass of the character, and it is not constrained to follow the center of pressure of the feet. This is because the IPC model is geometrically mapped to a full-body human pose as reference motion~~s~~. Without explicit constraints on the center of pressure, the control algorithm for the IPC model is contact-independent. We adopt the same IPC controller because this property enables easy manipulation of stride frequency and contact timing which is critical for simulating locomotion at different gravity.

Motivated by these works, we also use a combination of the IPC model for motion planning, a quadratic program for per-frame tracking, and an offline controller optimization. Our goal differs in that we generalize a reference motion to the completely different environments of the Moon, Mars, Neptune, and Jupiter.

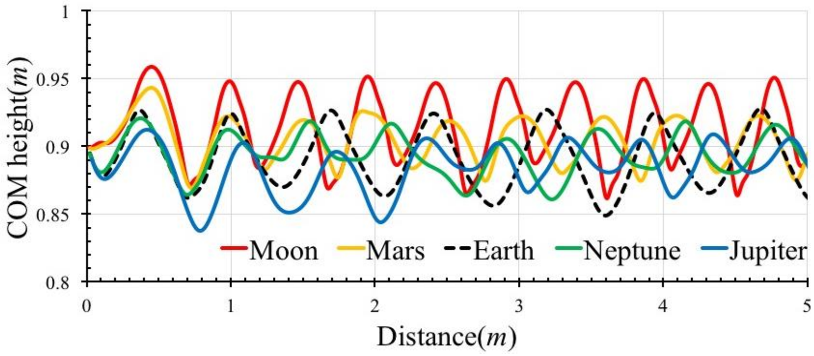
6.3. Quantitative Analysis

We measure the average COM forward velocity, the stride frequency, and the stride length of our simulated characters, as shown in Table 2. The simulated motions show lower velocities and stride frequencies and shorter stride lengths in lower gravity except running motion, where we increase its velocity to maximum to create visually pleasing results. On the other hand, in Neptune's gravity, the simulated motions show higher velocities and higher stride frequencies except turning motion. Turning motion shows lower velocities in Neptune's gravity and it is not stably generated in Jupiter's gravity. The human body shakes considerably from side to side and fell down easily because the rotation angle in the cycle of the motion is 180 degrees in motion states of turning motion and Jupiter's gravity is much higher than Earth's gravity. These two factors lead to losing the balance of the character body; i.e. the turning motion is strongly influenced by gravity.

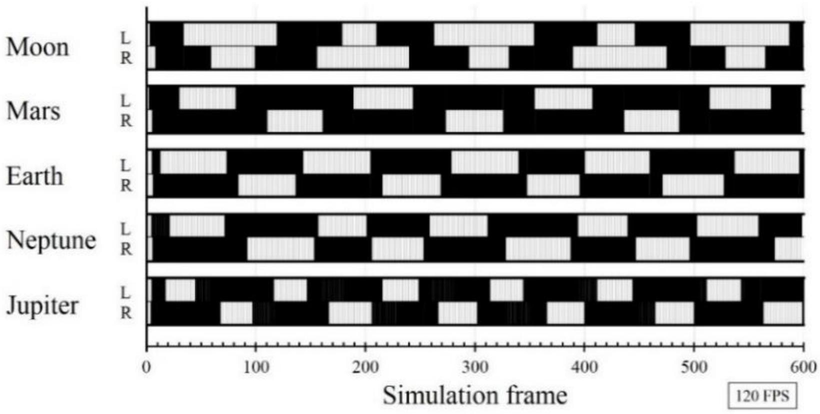
Table 2. Average COM forward velocity $\mathbf{v}$ in $\mathbf{m/sec}$, average stride frequency in $\mathbf{1/sec}$ and average stride length in $\mathbf{m}$ in our simulation under different gravity conditions.

Gravity	Walking			Running			Turning		
	v	StFreq	StLen	v	StFreq	StLen	v	StFreq	StLen
Moon	0.50	0.52	0.96	1.09	0.54	2.05	0.51	0.66	0.78
Mars	0.80	0.74	1.08	1.10	0.63	1.75	0.58	0.66	0.87
Earth	1.28	0.89	1.44	0.97	0.93	1.05	0.70	0.85	0.82
Neptune	1.30	1.01	1.25	1.07	1.26	1.35	0.42	0.84	0.73
Jupiter	1.32	0.76	1.06	0.91	1.31	1.22			

Walking motion: The lower the level of gravity is, the higher the COM height becomes, as shown in Figure 16-(a). As we set the COM forward velocity lower in lower gravity, the stride length becomes shorter and the period of walking motion becomes longer except Jupiter's gravity, as shown in Table 2. The duty factor gets similar to each other except the Moon's case, as shown in Figure 16-(b). This difference is caused by the flight phases on the Moon. The ground reaction forces in Mars' and the Moon's cases decrease by 65 % and 75 % compared to that of Earth and the ground reaction forces in Neptune's and Jupiter's cases increase 15 % and 130 %. In case of the Moon, even if the character moves slowly with a small amount of joint torques, the character reacts to the ground reaction forces rather sensitively due to the reduced gravity, which causes a more frequent flight phases.



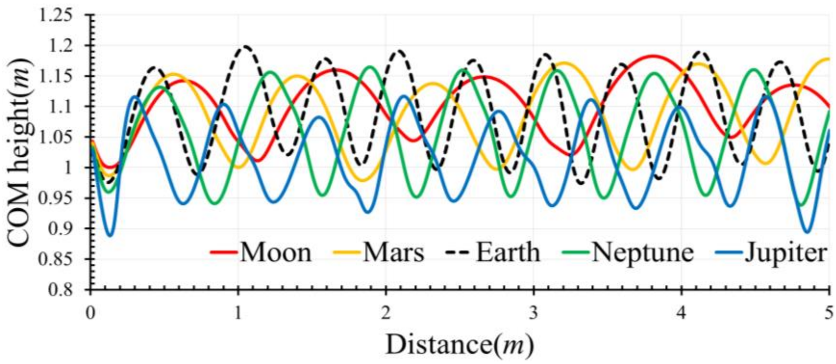
(a) COM height



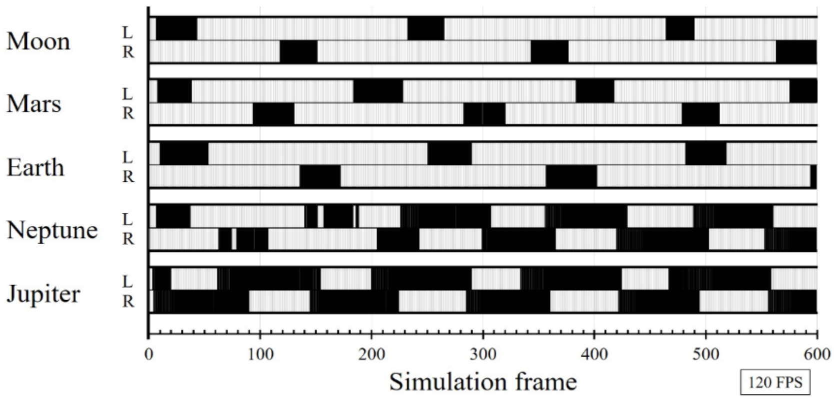
(b) Foot contact states

Figure 16. COM height and foot contact states of walking motions in altered gravity. (a) COM height with respect to distances in different gravity. (b) Foot contact states with respect to simulation frame for walking motion in different gravity. L is the left foot and R is the right foot. The contact phases are colored in black.

Running motion: As shown in Figure 17-(b), the periodicity of the COM height for three different gravitational conditions is formed at approximately 1.08 m. At the same COM forward velocity, the lower a level of gravity is, the longer the stride length becomes except Jupiter's gravity; see Table 2. The period of motion also becomes longer in lower gravity. The duty factors are similar to each other and the occurrences of flight phases for one running stride are similar in reduced gravity as shown in Figure 17-(b), but the ground reaction forces are different; the ground reaction forces in Mars' and the Moon's cases decrease by 26 % and 59 % compared to that of Earth and the ground reaction forces in Neptune's and Jupiter's cases increase by 41 % and 54 % compared to that of Earth. As a level of gravity increases, the running motions become walking motions.



(a) COM height

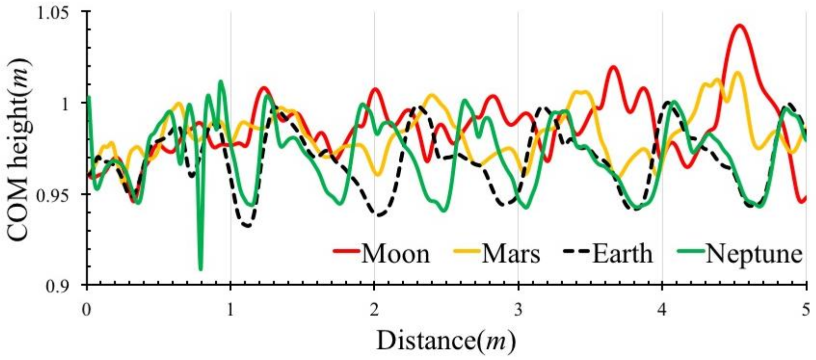


(b) Foot contact states

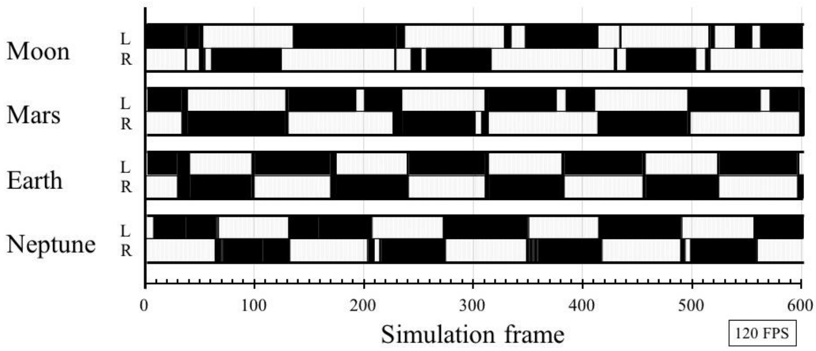
Figure 17. COM height and foot contact states of running motions in altered gravity. (a) COM height with respect to distances in different gravity. (b) Foot contact states with respect to simulation frame for walking motion in different gravity. L is the left foot and R is the right foot. The contact phases are colored in black.

Turning motion: The COM trajectory of turning motion is regular, as the character balances itself on one stance hip while swinging the other leg. We set the COM forward velocity low when the gravity decreases from Earth's gravity. As the COM forward velocity lowers, the COM height becomes higher, as shown in Figure 18-(a), and the turning radius of the COM trajectory becomes bigger starting from 1 m in Earth to 2.5 m in Mars and 3.5 m in the

Moon. The radius under Neptune's gravity increases by 1.66 m. As shown in Figure 18-(b), the period of motion also increases in reduced gravity. Regardless of the velocity or gravity, the duty factor is almost unchanged. Although the ground reaction forces in Mars' and the Moon's cases decrease by 65 % and 80 % compared to those in Earth, the flight phases occur more frequently than the cases of walking motions in reduced gravity. On the other hand, in higher gravity, the flight phases occur in Neptune's gravity. The ground reaction force in Neptune's gravity increase by 170 % compared to that of Earth.



(a) COM height



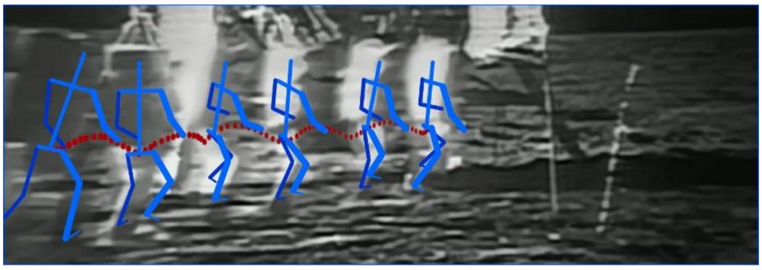
(b) Foot contact states

Figure 18. COM height and foot contact states of turning motions in altered gravity. (a) COM height with respect to distances in different gravity. (b) Foot contact states with respect to simulation frame for walking motion in different gravity. L is the left foot and R is the right foot. The contact phases are colored in black.

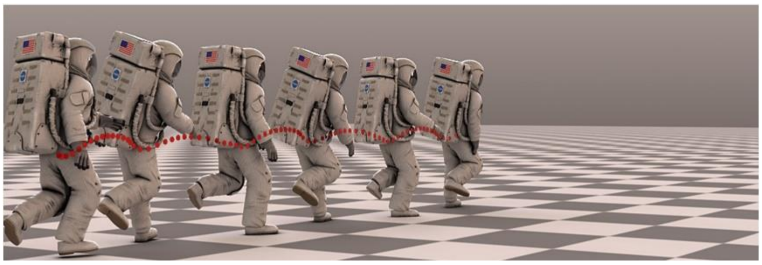
Comparisons with ground truth: We compare the similarity between our simulated motions and the real video footage of a bipedal motion, that was captured by the NASA in the late 1960s during the Apollo missions. In particular, we use the video clip provided by the NASA and available on the YouTube website (https://youtu.be/S9HdPi9Ikhk?t=54m21s). The Motion starts from 54 minutes 21 seconds (Figure 19-(a)), and lasts for 5 seconds in the video clip. We show the sequences of this live footage and of our simulated motion to compare each other in Figure 19-(a) and (b), We also show the COM trajectories for both the simulated motion and the real astronaut motion in Figure 19-(c). According to this experiment, the COM forward velocity, the stride frequency, and the stride length have only about 1~5% relative differences (Table 3), even considering the fact that the simulation environment is only approximate to the Apollo mission. Our simulated motion visually matches with these ground truth sequences as well.

Table 3. Average COM forward velocity $\mathbf{v}$ in $\mathbf{m/sec}$, average stride frequency in $\mathbf{1/sec}$ and average stride length in $\mathbf{m}$ for the real astronaut motion and our simulated running motion under the Moon's gravitational condition.

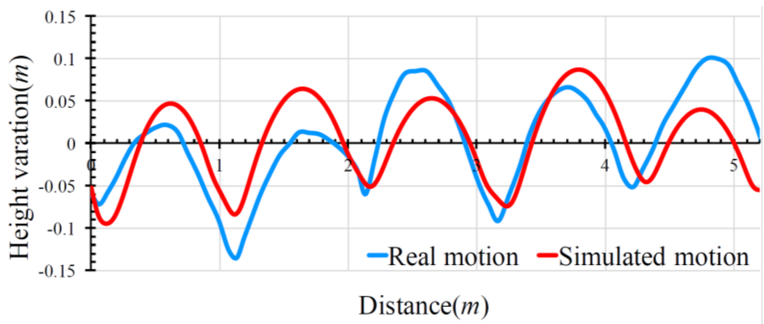
	v	StFreq	StLen
Real motion	0.50	0.52	0.96
Simulated motion	0.80	0.74	1.08



(a) The running astronaut motion, annotated with body skeletons in blue and the COM trajectory in red.



(b) Our simulated running motion in the Moon's gravity, annotated with the COM trajectory.



(c) The COM height variation with respect to the run distance for the real and simulated motions.

Figure 19. Comparison of our simulated running motion in the gravity of the Moon against the Apollo 11 video footage.

VII. Conclusion

In this dissertation, we have proposed a physics-based approach to simulate the full-body human locomotion in altered gravity. Since we do not have reference motions in altered gravity, we make an assumption that the human movement on other planets would be similar to that on Earth. Based on the Froude number, which is largely used to describe a gait pattern in biomechanical research, we have designed a pre-estimation model to predict the desired velocity of our character model for various gravity environments. This approach generates full-body animation for a human character using IP generation, motion planning and tracking in sequence. In our experiments, we successfully demonstrate that our simulation can generate robust and realistic full-body animation of various gaits under different gravitational conditions.

Our method generates robust and natural motions in different environments. The proposed controller makes stable and robust locomotion for an inclined plane and against external perturbations. We verified that our controller generates natural and valid locomotion by comparing to real locomotion sequences from the Apollo mission. Our running motion on the Moon resembles the real running motion in the Apollo 11 clip. We also compare our simulated motions with an analytical model, and our result has a similar the mathematical gait model using the Froude number in altered gravity. We show that our technique is applicable to human locomotion with different gait patterns including walking, running, and turning under altered gravity environments.

As for future work, we would like to design a control system that can automatically generate human locomotion in any gravity environments. Our current system requires a user to manually modify gait variables, COM velocity, and stride frequency. Thus, automating the settings for these three components will enable us to study the gradual changes in human locomotion. We would also like to design our system to produce smooth walk-run transition with any gravity environments. Our system regenerates simulated motions with the same gait styles of captured motions because we define human locomotion using motion states (i.e. hip swing/stance) for each gait style and we assume that the gait pattern of captured motions keeps itself although gravity is altered. It can allow us to produce dynamic gait styles from the captured motions and understand the reason why an astronaut on the Moon hops or moves with asymmetric gait style. Thus, it can make it possible to derive a more complex rule of human locomotion in altered gravity than the Froude number and to study exact mechanical energy fluctuations and exchanges during biped movements.

We look forward to using our simulated motions in applications including video games, animations, or films. We also expect that the resulting biped motions are usable in building educational programs and training programs. Our work may enable people to explore satellites or planets virtually and be able to provide a host of opportunities to help prepare astronauts for their mission as more precisely simulating motions helps not only in quickly adapting to different environments but also reducing training time to adapt to the gravity changes.

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국문초록

김윤형
컴퓨터공학과
이화여자대학교 대학원

인체 동작과 중력 사이의 관계를 이해하기 위해 중력 환경 시뮬레이션이 과거에 다양하게 연구되었다. 그 중에서 물리기반 시뮬레이션은 저비용으로 인체 동작을 정밀하게 측정할 수 있으며, 공간적 제약이 없어 다양한 동작을 생성하는데 용이하다. 그러나 기존의 저중력하의 물리기반 인체 동작 시뮬레이션은 하체 동작에 집중되어 있으며, 그 또한 대부분 지구 중력 환경에 대해서만 연구가 이루어졌다.

본 논문에서는 물리 기반 접근법을 통해 다양한 중력 환경에서의 사람의 전신 동작 시뮬레이션을 제안한다. 다양한 중력 환경에서의 전신 동작 시뮬레이션 시스템을 개발하기 위해서는 캐릭터의 높은 자유도 제어와 다양한 중력 환경에서 인체 동작 데이터의 부족 문제 그리고 자연스럽고 견고한 동작 생성 문제가 고려되어야 한다. 본 논문에서는 중력이 동작에 미치는 영향을 고려하여 물리기반 접근법을 통해 주어진 중력에 따라 사람 동작을 직관적이며 효과적으로 제어하는 방법을 제시한다.

제안한 시스템은 참조 동작으로 지구 중력에서의 걷기, 달리기, 회전 동작을 사용한다. 테스트 중력 환경으로 달, 화성, 해왕성, 목성 환경을 구성했으며, 이를 통해 점진적으로 변하는 중력 크기에 따라 사람 동작의 변화 추이를 살필 수 있도록 했다. 제안된 시스템에서는 프루드 수(the *Froude number*) 기반의 예측 모델을 통해 주어진 중력에 대해 캐릭터 이동 속도와 동작 주기를 예측하여 시스템에 적용한다. 이를 기반으로 시스템은 카트형 역진자 (IPC) 모델을 사용해 무게 중심 궤적을 생성하며, 발걸음 동작 계획법을 바탕으로 전신 동작 궤적을 합성한다. 그 결과로 변화된 중력 환경에 적응한 전신 동작 애니메이션이 생성된다. 시

뮬레이션 결과에 따르면 중력이 감소할 경우에 걷기 동작에서 전진 속도와 보폭 주기 그리고 보폭 길이 모두 감소하는 경향을 보이며, 달리기 동작에서는 전진 속도가 유사하고 보폭 주기는 감소하며 보폭 길이가 증가하는 결과를 보였다. 그리고 회전 동작에서는 전진 속도와 보폭 주기가 감소하고 보폭 길이가 유사함을 확인 할 수 있었다. 최종적으로 기존 시뮬레이션 시스템과의 비교를 통해 본 논문에서 제안된 방법이 인체 동작을 보다 효과적으로 생성함을 보였다. 또한, 아폴로 달 착륙 영상에서의 우주인 동작과 시뮬레이션 동작을 비교하여 애니메이션 품질이 우수함을 보였다.

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