2014 IEEE International Conference on Robotics & Automation (ICRA)
Hong Kong Convention and Exhibition Center
May 31 - June 7, 2014. Hong Kong, China

Running Model and Hopping Robot Using Pelvic Movement and Leg Elasticity

T. Otani, M. Yahara, K. Uryu, A. Iizuka, K. Hashimoto, T. Kishi, N. Endo, M. Sakaguchi, Y. Kawakami, S.H. Hyon, H.O. Lim and A. Takanishi, *Member, IEEE*

Abstract— **Human running motion can be modeled by a spring loaded inverted pendulum (SLIP). However, this model, despite being widely used in robotics, does not include human-like pelvic motion. In this study, we show that the pelvis actually contributes to the increase in jumping force and absorption of landing impact, both of which findings can be used to improve running robots. On the basis of the analysis of human running motion, we propose a new model named SLIP^2 (spring loaded inverted pendulum using pelvis). This model is composed of a body mass, a pelvis, and leg springs; the model can control its springs during running by use of pelvic movement in the frontal plane. To achieve hopping and running motions, we developed pelvis oscillation control, running velocity control, and stabilization control using an upper body, as control methods. We also developed a new hopping robot using the SLIP^2 model. To evaluate the proposed model and control methods, we performed hopping and running simulations. The simulation results showed that the SLIP^2 model successfully achieves hopping and running motions. The hopping robot was also able to accomplish hopping motion. The simulation results also showed that the difference between the pelvic rotational phase and the phase of oscillation of the mass vertical displacement affects the jumping force. In particular, the results revealed that the human-like pelvic rotation contributes to the absorption of landing impact and to the increase in takeoff forces, which validates our observations in human motion analysis.**

This study was conducted with the support of the Research Institute for Science and Engineering, Waseda University; Institute of Advanced Active Aging Research, Waseda University and as part of the humanoid project at the Humanoid Robotics Institute, Waseda University. It was also supported in part by the MEXT/JSPS KAKENHI Grant No. 25709019; Suzuki Foundation; Grants for Excellent Graduate Schools, MEXT, Japan; SolidWorks Japan K.K.; DYDEN Corporation and Cybernet Systems Co., Ltd.; we thank all of them for the financial and technical support provided.

Takuya Otani is with the Graduate School of Advanced Science and Engineering, Waseda University, and is a Research Fellow at the Japan Society for the Promotion of Science, #41-304, 17 Kikui-cho, Shinjuku-ku, Tokyo 162-0044, JAPAN (e-mail: contact@takanishi.mech.waseda.ac.jp).

Masaaki Yahara, Kazuhiro Uryu, Akihiro Iizuka and Tatsuhiro Kishi are with the Faculty of Science and Engineering, Waseda University.

Kenji Hashimoto is with the Research Institute for Science and Engineering, Waseda University.

Nobutsuna Endo is with the Faculty of Engineering, Osaka University.

Masanori Sakaguchi is the Faculty of Kinesiology, University of Calgary, Canada.

Yasuo Kawakami is with the Faculty of Sport Sciences, Waseda University.

Sang-Ho Hyon is with the Faculty of Science and Technology, Ritsumeikan University.

Hun-ok Lim is with the Faculty of Engineering, Kanagawa University, and is a researcher at the Humanoid Robotics Institute (HRI), Waseda University.

Atsuo Takanishi is with the Department of Modern Mechanical Engineering, Waseda University, and is the director of the Humanoid Robotics Institute (HRI), Waseda University.

I. INTRODUCTION

Several researchers have performed motion capture experiments to realize human motion. In some cases, however, these experiments pose a risk of injury, because of which it is not possible to perform them. To resolve this problem, we, the Waseda University research group, have proposed that a biped humanoid robot that can mimic human motion is useful for the research of human science and sports science. When the humanoid robot realizes human-like motion or uses instruments, we can measure various data of the robot's motion and compare human-like motions with those that do not mimic humans. This measurement and comparison will be useful for the verification of human motion's characteristics and testing instruments.

We have previously developed a biped humanoid robot named WABIAN-2R (WAseda BIpedal humANoid – No. 2 Refined) to mimic human motion and mechanisms. Its height is 1480 mm and weight is 63.8 kg, and it has 41 DOF (degrees of freedom). WABIAN-2R can perform a stretched knee gait with a 2-DOF (roll, yaw) pelvis [1-3]. However, this robot is limited only to walking.

Recent research on biped humanoid robots has contributed a few running robots. For example, ASIMO can run at a speed of 9 km/h [4]. Further, Toyota's biped humanoid robot can also run, using a ZMP (zero moment point)-based running control system [5]. Niiyama et al. developed the athlete robot, which has a human-like musculoskeletal system built to achieve dynamic motion such as running [6]. The biped robot MABEL has leg elasticity that originates from a flat spring, and it can run the fastest out of all the presently available biped robots, attaining a speed of 11 km/h with axial constraints on the Y-axis [7]. However, none of these robots mimic human running characteristics.

Some important characteristics of human running have been identified by researchers in the field of sports science and biomechanics, such as head stabilization [8], moment compensation using the upper body and arms [9], and leg stiffness [10]. However, an important characteristic that has not yet been reported is that a human's pelvic movement in the frontal plane can help to increase takeoff forces and absorb landing impacts. In this paper, we report this finding on the basis of an analysis of human motion. Then, based on this finding, we propose a running model that is a combination of a traditional SLIP (spring loaded inverted pendulum) model and a pelvis. The proposed model, called SLIP^2 (spring loaded inverted pendulum using pelvis), is composed of a body mass, a pelvis, and leg springs. We then describe running control and a hopping robot using the SLIP² model. We also discuss the influence of the pelvis on the absorption of landing impact and increase in takeoff force. We successfully simulated hopping and running motions using SLIP², and completed a hopping experiment with a real hopping robot. We present these simulations and experiment here.

This paper is organized as follows. In section II, we describe human pelvis rotation, the SLIP² model, and running control methods. In section III, we describe the development of the hopping robot, and in section IV, we present experimental results. Finally, in section V, we present the conclusions and discuss future work.

II. Development of SLIP² Model and Running Control

A. Pelvic Movement Analysis

In an attempt to identify the characteristics of human running motion that could be useful for robot design, we conducted a series of motion capture experiments with human subjects. We asked three subjects (gender: male, height: 1730 ± 70 mm, weight: 61 ± 9 kg) to perform regular running motion and measured the data 10 times for each subject. The results suggested that pelvic movement in the frontal plane could aid human running.

Fig. 1 shows the average pelvic movement in the frontal plane during the stance phase of running at 4 m/s. The pelvis levels off at an angle of 0deg. The measurement shows that the angle of the pelvis is 5.9deg at heel strike-the idling leg is lowered at this point. The pelvis then rotates up to 6.9deg until landing of the sole. Next, the idling leg lowers down. After that, the pelvis rotates in the opposite direction up to -5.1deg until takeoff using the toe. That is to say, the pelvis rotates to lower the idling leg, and then rotates in the opposite direction to raise it. From this result, we assume that the pelvic movement in the frontal plane can help to increase the takeoff force and absorb the landing impact. The pelvis movement at landing can help to absorb the landing impact, and the subsequent movement can help to increase the takeoff force.

B. SLIP² Model

In previous works, human running was modeled as SLIP [10], whereas human walking was modeled as an inverted pendulum [4]. The SLIP model is composed of a body mass and a spring leg and is based on the linear relationship between the ground reaction force and the vertical displacement of the body during running [11] [12] [15]. In this model, in the flight phase, human movement is modeled as a parabolic motion of a mass point. This model describes human running in a simple, straightforward way. However, humans lose energy by landing impact and owing to the leg's muscles. This lost energy should be compensated for by an actuator, which was assumed to be the leg's muscle in previous studies. However, in terms of similarity with the actual human body, the SLIP model does not model the pelvis. Based on the human motion analysis presented in the previous section, we propose a new model, SLIP² (shown in Fig. 2), which is composed of an upper body, a pelvis, and spring legs. During stance, human motion is modeled by SLIP², whereas during flight, it is modeled as a parabola.

C. Pelvis Oscillation Control

The pelvis oscillation control method is used for storing energy. In this method, the pelvis is controlled using the natural frequency calculated from the mass weight and leg stiffness in the stance phase, with the objective of attaining sufficient jumping power. The hip roll axis is controlled to equal the pelvis roll axis and keep the leg vertical. The pelvic movement is modeled as a linear displacement, and the motion equation of the Z-axis is given by

$$m\ddot{z}_m(t) + k(z_m(t) - l_s - l_p(t) - l_a(0) - l_k(0)) - mg = 0 \quad (1)$$

where m is the mass; $z_p(t)$, the vertical displacement of the mass; $l_p(t)$, the vertical displacement of the pelvis; $l_k(t)$, the leg spring's length; $l_a(0) = 0$, the leg actuator's length; k, the leg stiffness; g, the gravitational acceleration (=9.8

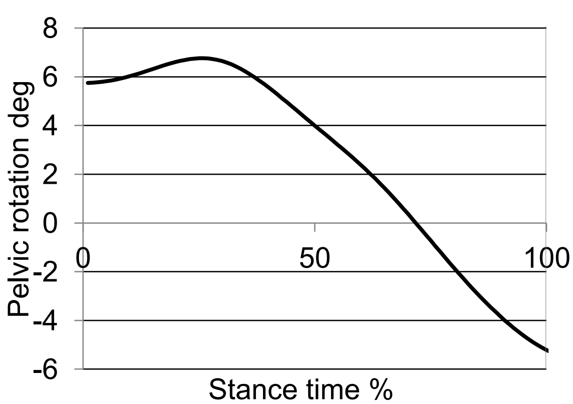


Fig. 1 Human pelvic rotation in the frontal plane during running. First, at heel strike, the angle of the pelvis is 5.9 deg. Then, the pelvis rotates up to 6.9° until landing of the sole. Subsequently, the pelvis rotates in the opposite direction up to -5.1 deg until takeoff using the toe.

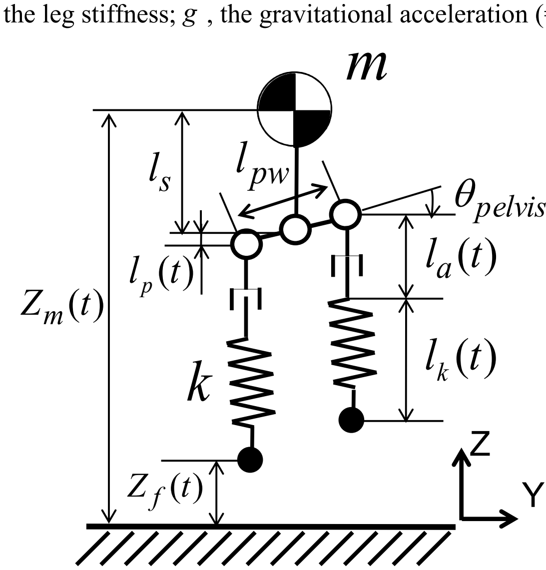
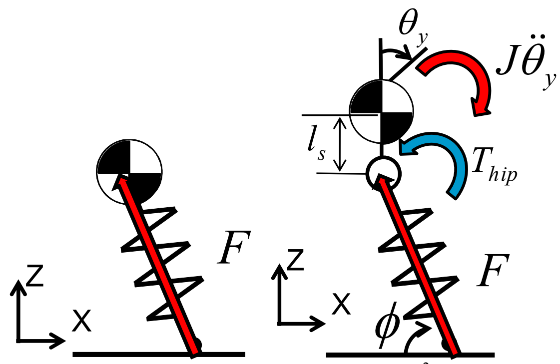


Fig. 2 Spring-mass model with pelvis joint (SLIP²)

m/s^2); and t , the time of the stance phase. The pelvis oscillation control is expressed as

$$\theta_{pelvis}(t) = \begin{cases} A\sin(\omega t) & \text{for } z_f(\mathrm{t}) = 0 \text{ (stance phase)} \\ 0 & \text{for } z_f(\mathrm{t}) > 0 \text{ (flight phase)} \end{cases} \quad (2)$$

where ω is the natural frequency and A is the pelvis rotation amplitude. In addition, the model can hop with both its legs by switching the support legs during the flight phase. However, if only the pelvis oscillation control is used, then the idling leg lands in the stance phase. To solve this problem, we control the linear actuator's length of the idling leg given by



(a) SLIP model (b) SLIP^2 model
Fig. 3 Stabilization using upper body

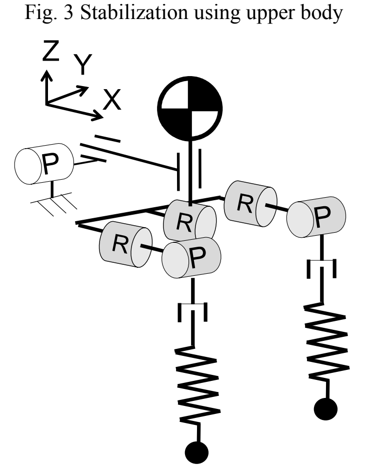


Fig. 4 Running model

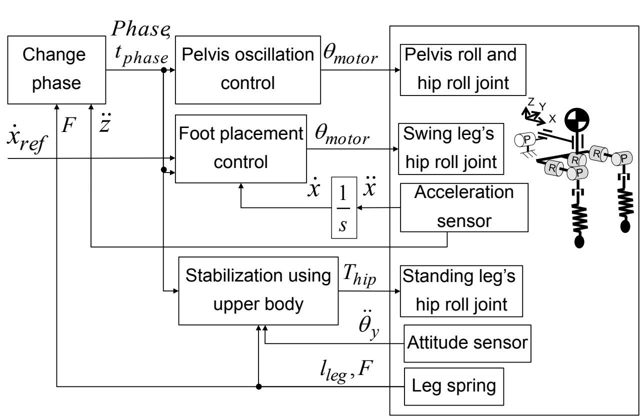


Fig. 5 Block diagram of running control

$$l_a(t) = \begin{cases} 0 & \text{for stance leg} \\ -0.2 & \text{for swing leg} \end{cases} \quad (3)$$

D. *Foot Placement Control*

We use foot placement control for running as used by Raibert [12], given by

$$x_f = \frac{\dot{x}T}{2} + K(\dot{x} - \dot{x}_{ref}) \quad (4)$$

where x_f is the foot placement, x is the mass placement, T is the stance time, $\dot{x}_{ref}$ is the reference running velocity, and K is the control gain.

In the SLIP model, the mass is located on the hip joint (Fig. 3(a)). A human's center of gravity is actually some distance away from the hip joint, meaning that a moment generated by the ground reaction force makes the model unstable. To overcome this problem, we developed a stabilization control method using the upper body to compensate for this moment, by controlling the hip joint in the stance phase (Fig. 3(b)). T_{hip} is the torque of the hip joint, and is given by the moment equation

$$T_{hip} = J\ddot{\theta}_y + Fl_s\cos\phi \quad (5)$$

where J is the body's inertia, θ_y is the body attitude, F is the ground reaction force, l_s is the distance from the mass to the pelvis, and ϕ is the touchdown angle. The running model is shown in Fig. 4, and the control block diagram is shown in Fig. 5.

III. Development of Hopping Robot

A. *Requirements for New Hopping Robot*

Next, we aim to develop a hopping robot that can successfully execute hopping motion using real hardware. We determined the requirements for velocity and torque in the hip roll joint on the basis of human running data acquired by Reed et al. [13]. We also fixed the requirements for the velocity of the pelvis roll joint based on human running data acquired by Schache et al. [14]. To the best of our knowledge, no work has previously been conducted on the torque of the pelvis roll joint. We calculated these requirements by substituting appropriate values in the motion equation (1). The requirements for the velocity and torque of the pelvis and hip roll joints are summarized in Table I.

B. *Design of New Hopping Robot*

We chose a 150-W DC motor (Maxon Co., Ltd.), a timing belt, and a harmonic drive to actuate the pelvis and hip joints. To adjust the mass, weights can be mounted on the upper part of the robot. As the leg's spring, we selected a compression spring, shaft, set collar, and linear bush. Owing to this mechanism, the compression spring is not detached from its upper and lower parts when the spring is free-length. In addition, we can change to other compression springs by adjusting the distance between the set collar and the linear bush. We fixed the range of the spring's stiffness based on previous research [15]. The robot motion is restricted to the vertical direction with linear guides. The developed hopping robot with a pelvis is shown in Fig. 6.

IV. EXPERIMENTS

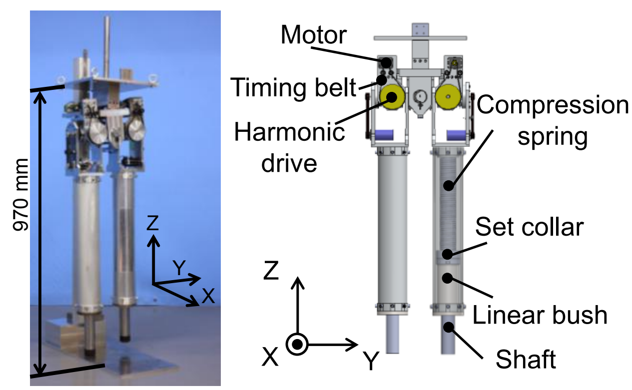
To evaluate the SLIP^2 model and the running control methods, we simulated them with a physical modeling and simulation tool, MapleSim (Cybernet Systems Co., Ltd.).

A. Hopping Simulation

We successfully performed a hopping simulation using the SLIP^2 model. The simulation result shown in Fig. 7, and the mass height in the hopping simulation is shown in Fig. 8. When the leg spring is free-length, the mass height is 1 m. Therefore, the jumping height from the ground is more than 0.04 m.

TABLE I
Requirements

	Pelvis roll joint	Hip roll joint
Max. velocity (rad/s)	2.29	1.24
Max. peak torque (Nm)	43.8	113
Max. average torque (Nm)	27.9	56.3



(a) Overview (b) Description
Fig. 6 New hopping robot with a pelvis and leg spring

TABLE II
Simulation parameters

Mass weight m (kg)	50
Distance from mass to pelvis l_s (m)	0.1
Pelvis width l_{pw} (m)	0.2
Leg length[a] $l_a(t) + l_k(t)$ (m)	0.9
Leg stiffness k (kN/m)	16
Pelvic rotation amplitude A (deg)	6.0

[a] Under the following conditions:
- Leg spring is free-length.
- Length of a leg's linear actuator is 0 m.

B. Difference in Pelvic Rotational Phase

As noted previously, the pelvis rotates to lower the idling leg, and then rotates in the opposite direction to raise it. From this information, we assume that the pelvic movement in the frontal plane during landing can help to absorb the landing impact, and that the subsequent movement can help to increase the takeoff force. However, this pelvic rotation to raise the idling leg is greater than the rotation required to lower it. This is because the pelvic rotational phase is different from the oscillation of the vertical displacement of the mass.

To analyze the influence of the difference in pelvic rotational phase on the absorption of landing impacts and the increase in takeoff forces, we performed simulations wherein the SLIP^2 model free-falls from the height of the foot from the ground, i.e., 0.1 m, and jumps using the pelvis oscillation control after

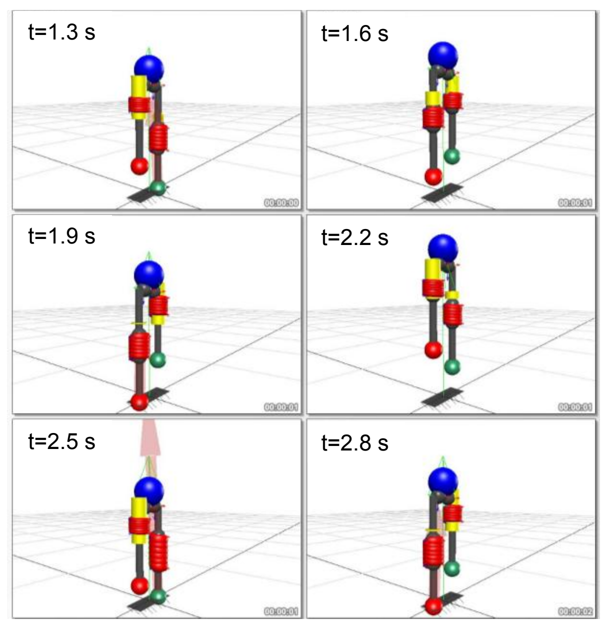


Fig. 7 Hopping simulation. Pelvis oscillation control starts at 1 s. The amplitude of the pelvis oscillation control is 6 deg.

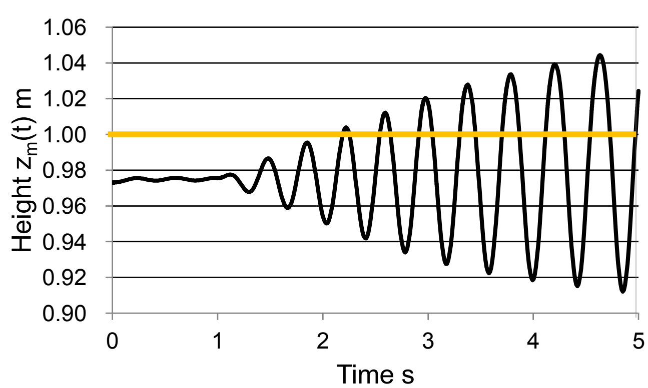


Fig. 8 Hopping height. When the leg spring is free-length, the mass height is 1 m. Therefore, the jumping height from the ground is more than 0.04 m.

landing. The pelvis oscillation control is expressed as

$$\theta_{pelvis}(t) = \begin{cases} A\sin(\omega t + \phi) & \text{for } z_f(\mathrm{t}) = 0 \text{ (stance phase)} \\ 0 & \text{for } z_f(\mathrm{t}) > 0 \text{ (flight phase)} \end{cases} \quad (6)$$

where the phase difference ϕ is 0, π/8, π/4, 3π/8, and π/2. The mass height is shown in Fig. 9, and its vertical acceleration is shown in Fig. 10. The jumping height increases with increasing phase difference of the pelvic rotation. Moreover, the maximum vertical acceleration of the mass increases with increasing difference of the pelvic rotational phase. In particular, the human pelvic rotation is similar to the phase difference of π/4. When the phase difference is π/2, the pelvis rotates to raise the idling leg without lowering. Comparison of these two cases shows that the maximum vertical acceleration of the mass with a π/4 phase difference is 6% less than that with a π/2 phase difference. This suggests that the difference in the pelvic rotational phase has an influence on the absorption of landing impacts and the increase in takeoff forces. In particular, the human-like pelvic rotation contributes to absorb landing impact and to increase takeoff force.

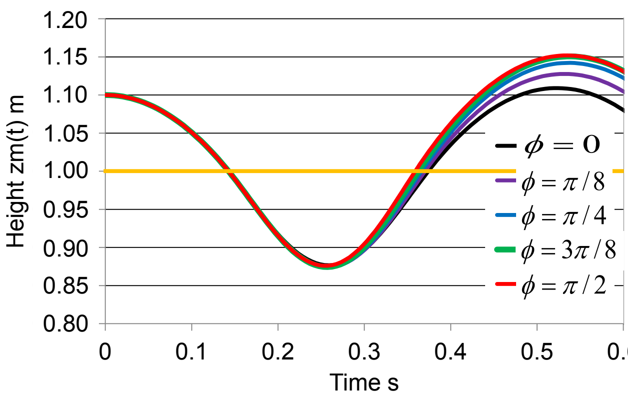


Fig. 9 Center of mass height in the simulation.

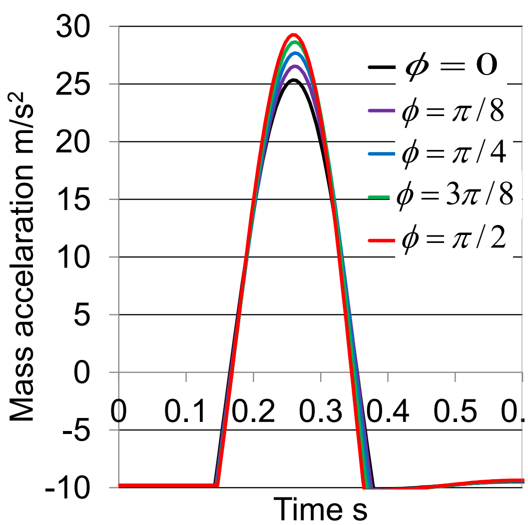


Fig. 10 Center of mass acceleration. The maximum vertical acceleration of the mass with the π/4 phase difference is 6% less than that with the π/2 phase difference.

C. *Hopping Experiment*

We performed a hopping experiment using the developed hopping robot. The conditions for the experiment were the same as those for the hopping simulation. Fig. 11 shows the results of the experiment, and Fig. 12 shows the mass height for the hopping experiment. The robot could not hop when the pelvis amplitude was 0.5deg. However, it could hop when this amplitude was 2deg.The mass height became higher as the amplitude became larger. However, when the amplitude was changed to 4deg, the height decreased after a number of jumps. We assume that this is because of the difference between the mass height and the pelvis oscillation. We had measured the mass height by a wire encoder, and used it to detect landing. However, the mass height became inaccurate when the robot jumped too high. In the future, we intend to improve landing detection by using a force sensor.

D. *Running Simulation*

Finally, we simulated running to evaluate the pelvis oscillation control and foot placement control with axial constraints on the Y-axis. Fig. 13 shows the simulation results, and Fig. 14 shows the transition of running velocity. From the reference running velocity (1.5 m/s in 5 s and 2.0 m/s in 5 s), we confirmed the effectiveness of the foot placement control.

V. Conclusions and Future Works

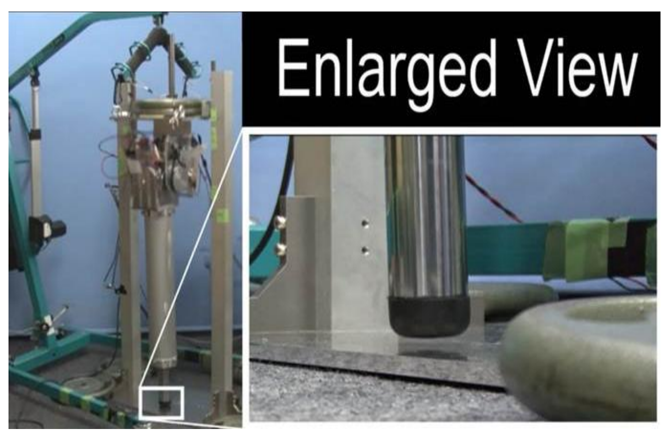


Fig. 11 Hopping experiment.

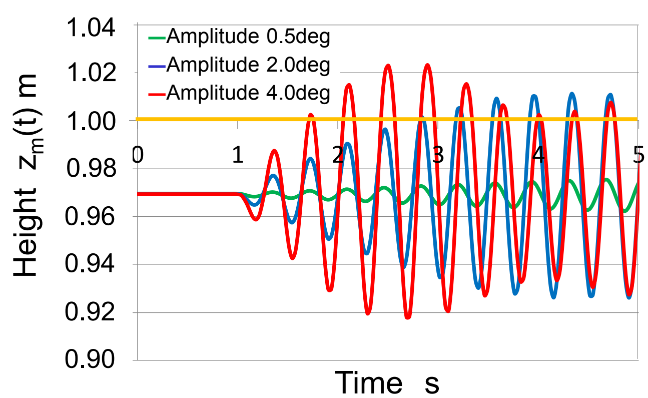


Fig. 12 Mass displacement during a hopping experiment. Pelvis oscillation was started at 1 s. When the leg spring is free-length, the mass height is 1 m.

In this paper, we described an analysis of human motion focused on pelvic movement in the frontal plane and the development of the SLIP^2 model and a running control scheme. From this analysis, we concluded that the pelvic movement in the frontal plane can help to increase takeoff forces and absorb landing impacts. We then developed a new model, called the SLIP^2 model, composed of the SLIP model and a pelvis, and running control methods, which include pelvis oscillation control, foot placement control, and stabilization control using the upper body. To evaluate the SLIP^2 model and the running control methods, we simulated hopping and running motions. We also developed a hopping robot using the SLIP^2 model and were able to successfully replicate the hopping experiment with a real robot. Moreover, we verified the influence of different pelvic rotational phases through simulations in using the SLIP^2 model. The results showed that the pelvic rotational phase difference has an influence on the absorption of landing impacts and the increase in takeoff forces. In particular, human-like pelvic rotation contributes to the absorption of landing impact and the increase in the takeoff force.

In the near future, we intend to model the pelvic movement in the horizontal plane. In addition, humans are able to run at high speeds because the moment generated by the ground reaction force and their leg movement are both compensated for by the use of their upper body and arms. We intend to combine the SLIP^2 model with an upper body to construct a new full-bodied model that will mimic this human characteristic. Finally, we will develop a new stabilization control method using the upper body and arms.

REFERENCES

[1] Y. Ogura, K. Shimomura, H. Kondo, A. Morishima, T. Okubo, S. Momoki, H. O. Lim and A. Takanishi, "Human-like Walking with Knee Stretched, Heel-contact and Toe-off Motion by a Humanoid Robot," Proc. 2006 IEEE/RSJ Int. Conf. Intelligent Robots and Systems, pp. 3976-3981, 2006.

[2] K. Hashimoto, Y. Takezaki, K. Hattori, H. Kondo, T. Takashima, H. O. Lim and A. Takanishi, "A Study of Function of the Human's Foot Arch Structure Using Biped Humanoid Robot," Proc. 2010 IEEE/RSJ Int. Conf. Intelligent Robots and Systems, pp. 2206-2211, 2010.

[3] K. Hashimoto, Y. Takezaki, H. Motohashi, T. Otani, T. Kishi, H. O. Lim and A. Takanishi, "Biped Walking Stabilization Based on Gait Analysis," Proc. 2012 IEEE Int. Conf. Robotics and Automation, pp. 154-159, 2012.

[4] T. Takenaka, T. Matsumoto, T. Yoshiike and S. Shirokura, "Running Gait Generation for Biped Robot with Horizontal Force Limit," JRSJ, Vol. 29, No. 9, pp. 93-100, 2011.

[5] R. Tajima, D. Honda and K. Suga, "Fast Running Experiments Involving a Humanoid Robot," Proc. 2009 IEEE Int. Conf. Robotics and Automation, pp. 1571-1576, 2009.

[6] R. Niiyama, S. Nishikawa and Y. Kuniyoshi, "Biomechanical Approach to Open-loop Bipedal Running with a Musculoskeletal Athlete Robot," Adv. Robotics, Vol. 26, Nos. 3-4, pp. 383-398, 2012.

[7] J. W. Grizzle, J. Hurst, B. Morris, H.-W. Park and K. Sreenath, "MABEL, A New Robotic Bipedal Walker and Runner," 2009 American Control Conf., pp. 2030-2036, 2009.

[8] T. Pozzo, A. Berthoz and L. Lefort, "Head Stabilization during Various Locomotor Tasks in Humans," Exp. Brain Res., Vol. 82, pp. 97-106, 1990.

[9] S. H. Collins, P. G. Adamczyk and A. D. Kuo, "Dynamic Arm Swinging in Human Walking," Proc. Biological Science, Vol. 276, pp. 3679-3688, 2009.

[10] T. McMahon and G. Cheng, "The Mechanics of Running: How does Stiffness Couple with Speed?" J. Biomech., Vol. 23, pp. 65-78, 1990.

[11] R. Blickhan, "The Spring-mass Model for Running and Hopping," J. Biomech., Vol. 22, No. 11, pp. 1217-1227, 1989.

[12] M. H. Raibert, "Legged Robots that Balance," Mass.: MIT Press, 1986.

[13] R. Ferber, I. M. Davis and D. S. Williams, III, "Gender Differences in Lower Extremity Mechanics during Running," Clin. Biomech., Vol. 18, No. 4, pp. 350-357, 2003.

[14] A. G. Schache, P. Branch, D. Rath, T. Wrigley and K. Bennell, "Three-dimensional Angular Kinematics of the Lumbar Spine and Pelvis during Running," Human Move. Sci., Vol. 21, pp. 273-293, 2002.

[15] G. Dalleau, A. Belli, M. Bourdin and J. R. Lacour, "The Spring-mass Model and the Energy Cost of Treadmill Running," Eur. J. Appl. Physiol., Vol. 77, pp. 257-263, 1998.

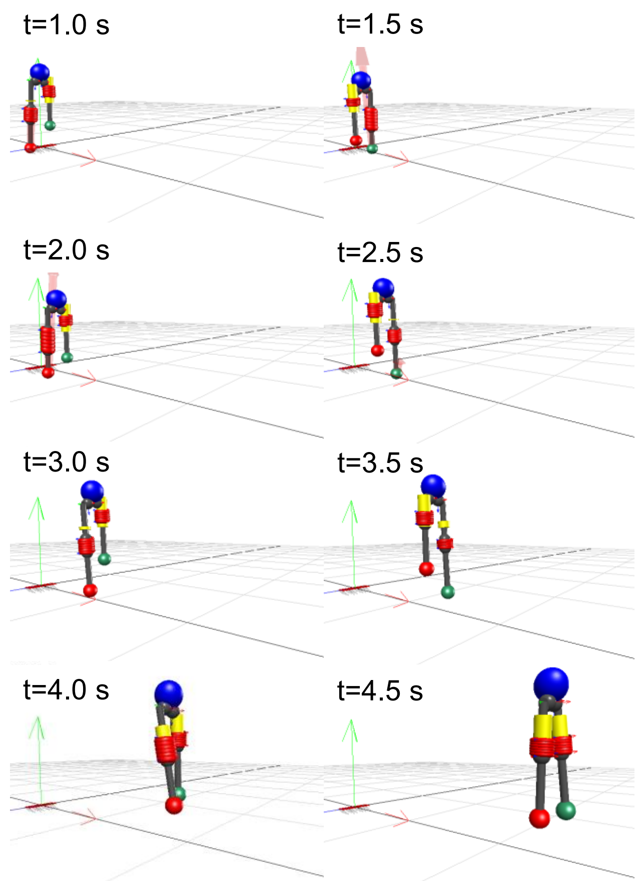


Fig. 13 Running simulation. The amplitude of the pelvis oscillation control was 6 deg.

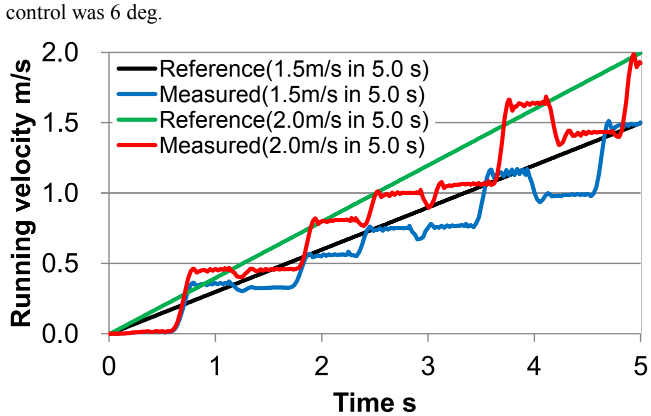


Fig. 14 Running velocity transition