Utilizing Physical Relationships for Biped Walking Control: a preliminary study in identifying key essential properties for the two support phases

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SYNOPSIS

In this paper, we present a simple controller for a planar biped walking system based on a compass-like biped model. It is well known that a walking cycle can be divided into two basic phases: a double support phase and a single support phase. We note the key essential elements for each support phase and determine their relationships throughout the walking cycle, and utilize them for stable walking control. This paper is structured in two parts. In the first part, the relationship between step length and initial push-off speed is explored and was utilized in the double support phase to correctly prepare for the consequence ballistic-like movement prior to leg swing. In the second part, the relationship between the states of stance leg and the hip joint angle was utilized to prepare for the following single support phase. This is use to regulate stability between the step length and the upper body speed in realizing the controller.

1 INTRODUCTION

Many biped robots have been developed; however, spontaneous motion generation and control for walking and standing still remain open problems. Humanoid robots such as P2 (HONDA) [1] and SDR-3X (SONY) [2] have demonstrated initial progress with stepping motion for recovery from a slight push backward; however, these perturbing slight pushes were gentle and gradual. One of the very few examples of accomplishing spontaneous motion on leg robots is Raibert's hopping robots [3]. These robots can continue to hop with large perturbations, even with hard pushes from the side.

These hopping robots make use of the relationship between the horizontal distance of its landing point and its hopping velocity after each step [3], as a neutral orbit [4] for control. Discovering the right (but simple) relationships with the real physical world – in order to utilize them – seems to be the key idea for spontaneous motion generation and control. This idea can also be seen in passive dynamic walking (PDW) [5]. In these systems the usage of the relationships are (in a sense) perfect, once the coupling are discovered these biped walkers require neither controller nor actuation. They are able to walk down a shallow slope utilizing only the effect of gravity, with walking motions that in many aspects resemble that of slow human walking. We believe natural looking motion generation and control like that of humans, are accomplished by maximizing the usage of key essential physical relationships, that lead to low control (computationally) cost and high-energy efficiency.

In order to identify key relationships within the physical world, our approach opts toward an investigation that explores passive dynamics and open-loop (partially passive) dynamics of mechanics with the environment, before implementing a controller.

It is well known that a walking cycle can be divided into two phases: a double support phase, and a single support phase. Each phase can be characterized with the following distinctive properties:

	Double support phase	Single support phase
Controllability	High (wide spreading contact area, a closed link)	Low (contact area is restricted with one foot, an open link)
Time period	Shorter (1/4 period of a cycle)	Longer (3/4 period of a cycle)

Table 1 Characteristics of double and single support phases in a human walking cycle.

The differences in these two support phases is reasonably large, therefore based on these distinctive characteristics, we propose suitable controllers for each phase.

2 DOUBLE SUPPORT CONTROL

The importance of the double support phase is in establishing stable condition before a consequence single support phase takes place. In humans, the single support phase that governs the controllability of the whole body's center of gravity (COG) in relation to external force/torque is strongly restricted by the foot size. The same situation can be seen in systems, such as a manipulator with passive joint, casting/pushing manipulation, brachiation robots, inverted pendulum, etc. These systems include some un-directly controllable degrees of freedom, referred to as under-actuated system. Due to such factors, preparing adequate states that will lead to a correct single support phase is utmost critical during double support.

Low controllability and the importance of initiation in human walking have been examined through the studies of ballistic walking [6]. In their research, a planer biped model stepped with a human-like motion, without any controller or actuator, except initial state settings. The two states to be initiated in the double support phase are velocity and position/orientation. In the case of a simple biped model, this means the setting of the initial push-off velocity with a corresponding step length. A relationship between step length and speed can be considered as longer step length demands greater push-off speed. We explore this relationship by the use of a dynamic simulator, DADS (a product of LMS International).

In our dynamics simulation, we used a compass-like biped model with fixed leg length, passive hip joints with no friction and viscosity. The model and parameters used in our simulation is same as the one used in our previous research [7]. (See Fig. 1)

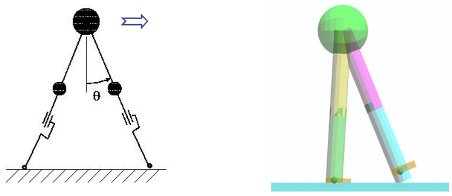

Fig. 1 Compass-like biped walking model and the model in the dynamic simulator.

Our studies is based on symmetrical stepping [8]; one step motion by setting only the initial speed of the upper body, rather than using leg/foot's pushing off motion. The initial leg angle taken from the vertical axis is used as the step length, because the step length and initial leg angle has a one to one mapping.

These systems are clearly affected by their mass distributions and leg lengths. In an attempt to explore/acquire the correct corresponding relationships, accounting for parameter differences, we performed numerous simulations by varying the parameters in Table 2 - all combinations were examined.

Mass of upper body [kg]	3.0, 4.0, 5.0
Mass of upper leg [kg]	6.0, 7.0
Mass of lower leg [kg]	3.0, 4.0
Mass of foot [kg]	1.0, 1.5
Upper/lower leg length [m]	0.3, 0.4, 0.5

Table 2 The varying physical parameters and its range for biped model.

For each parameter combination, the initial condition for symmetric gait is derived by searching for the adequate initial velocity s_0, for each given initial leg angle θ_0.

Initial leg angle θ_0 [rad]	0.01, 0.02, 0.03, …, 0.38, 0.39, 0.4, 0.45, 0.5

Table 3 Variations of initial leg angle.

The correct push off speed and the corresponding step length is searched iteratively through dynamic simulations. Large numbers of initial condition (step length and push off speed) for a variety of body parameters were explored (Fig. 2). These values were chosen to cover the standard body parts mass and gait variations of average adults [9][10].

It is known that a double pendulum in a plane aligned with the gravity field moves chaotically, like the three body problem. In detail, a Hamiltonian system that has two or more degrees of freedom, such as a multiple pendulum, is not integrable. That is, it is impossible to solve analytically the biped's differential equation of motion. As a result, we have chosen to investigate the problem empirically through physical simulations. With collected data, we performed curve fitting to derive a parametric model of the relationship between step length and push-off speed. The derived equation is based on an inverted pendulum with an inertial parameter α , which corresponds to the difference of the mass distribution between the actual model and a pure inverted pendulum.

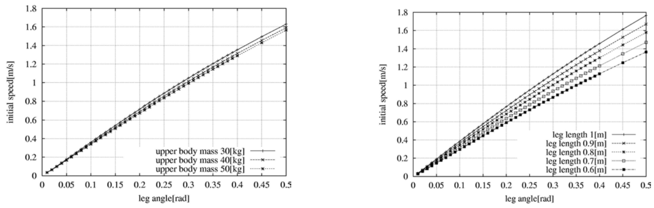

Fig. 2 The relationships between leg angle (x axis) and initial body speed (y axis). See also Fig. 3. The left figure shows the divergence on mass distribution (upper line is bottom heavy). The right figure shows on the leg length (upper line is long leg).

Empirical equation of the relationship between initial leg angles θ_0 and initial upper body speed s_0 is as follows:

$$s_0 = a\sqrt{gl\alpha(1-\cos\theta_0)} \ ,$$

where $\alpha = I_a/I_v$, a=0.756123.

g [m/s^2]	Gravitational acceleration constant
l [m]	Length of a whole leg.
I_a [kg m^2]	Inertia moment of whole body. The rotation axis is at foot point.
I_v [kg m^2]	Inertia moment of virtual Inverted Pendulum, such as whole body weight concentrates on the top. The rotation axis is at foot point.

Table 4 Parameters description for the equation that provides the relationship between step lengths and push off speed.

The adjustment coefficient a (in this case, it is equal to 0.756123) has been chosen to minimize the sum of square error between the derived empirical equation and the results of dynamic simulations.

This equation can derive the desired push off speed for control in the double support phase.

3 SINGLE SUPPORT CONTROL

In the previous section, an investigation of passive dynamics of compass-like biped during double support was considered. However, to allow gait variations and to increase stability beyond passive dynamic walking, such as controlling the step length and walking speed outside of just constant steady walking-controls during the single support phase needs to be examined.

During the single support phase, control of whole body motion (controlling the kinetic energy of COG by external force and torque) is difficult due to the under-actuation of the physical structure [11]. However, through hip actuation, the swing leg can control the step length during the single support phase, and the desired landing speed would be a mirror of the desired push off speed [13]. Therefore, we can exploit this relationship in selecting a step length for landing, which can produce the desirable effect that will lead to a correct push-off condition, thus helping to the stabilize consecutive steps [12].

In the case of active walking, we can utilize extrapolated desirable conditions from the original passive dynamics in our new controller. In the investigation of passive dynamics, hip joint angle has a cosine wave-like profile. Thus, we can make use of a cosine wave to generate the desired trajectory for a simple servo controller [13], which can be applied at the hip joint angle φ. The frequency f and amplitude φ_0, corresponds to a one step period for a particular step length, can be adjusted to derive the desirable symmetric step. The parameter φ_0 in the following equation is same as the initial leg angle θ_0 in the previous section - for the case of a constant step length:

$$\varphi = 2\varphi_0 \cos(2\pi f t).$$

To cope with perturbations, the parameters φ_0 and f should be adjusted based on the state of the body. For the design of the controller, we would need to derive a mapping between the stance leg states to swing leg angles (hip joint angle). Again, an empirical method was used to derive these equations for the mapping, which can be utilized by a swing leg servo controller.

The procedure to acquire the data sets for the derivation of the empirical equations and parameters is as follow:

1. A set of desired hip actuation parameters was selected: Frequency (f), Amplitude (φ_0).
2. Extensively search for desirable corresponding initial push off speeds (s_0) via dynamic simulations, for successful symmetrical stepping.
3. Iterate the above procedure with different combinations of parameters.

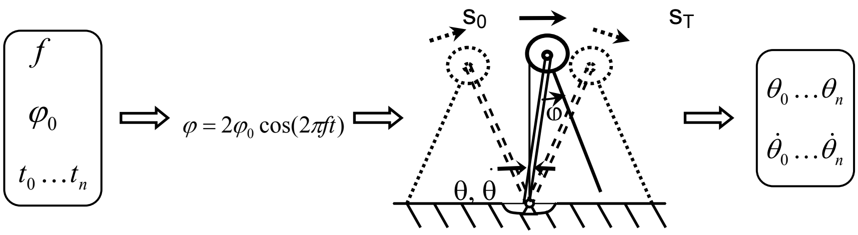

Fig. 3 The procedure to acquire the data sets for each combination of parameters including time.

From the data sets (Fig. 4) and through least square function fitting, we derived the following empirical equations:

$$t = (b_1/f)\phi^5 + (b_2/f)\phi^3 + b_3\phi + (b_4/f),$$

where $\phi = \tan^{-1}(\theta/\dot{\theta})$, b_1=0.250865535, b_2=0.99923389, b_3=3.94237392, b_4=37.364554.

$$\varphi_0 = \frac{c_1\theta_0\dot{\theta}}{\sqrt{\frac{c_2\theta^2}{f\sqrt{\theta_0}} + c_3 f - \sqrt{c_3 f} + c_4(f - c_5)\theta_0}},$$

where c_1=1.01470947, c_2=2.2453125, c_3=0.0398542766, c_4=4.61328125, c_5=0.23742125.

These coefficients are chosen to minimize the sum of squared error between the result of the empirical equation and the result of the dynamics simulations. The current derivation of amplitude φ_0 also includes the initial angle of single support phase θ_0. We are now searching for another parametric model in an attempt to remove θ_0.

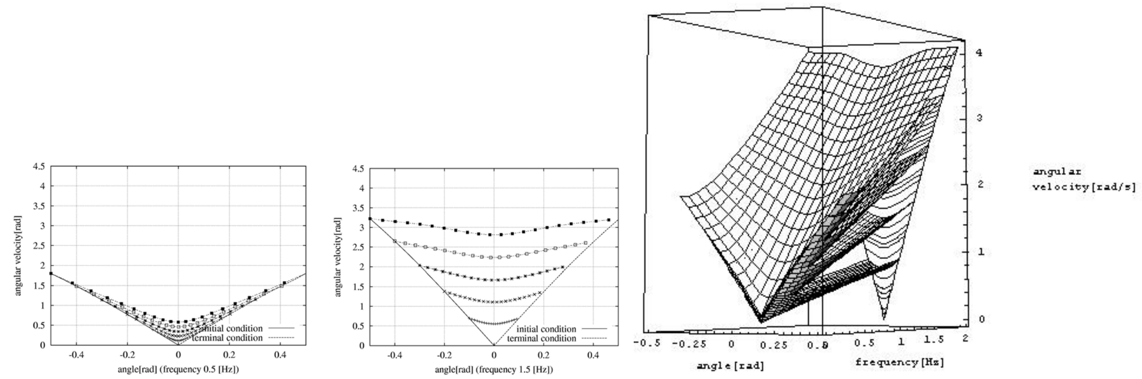

Fig. 4 Examples of the phase plots of the stance leg for each different frequencies (0.5, 1.5[Hz]), and combined 3D image of the phase plots. The initial (left) and terminal (right) condition curves, and transition curves between them. The x axis represents the angle of the stance leg, and y axis is the angular velocity. The initial/terminal condition curves increases with step frequency (see Section 2).

In the above equations, time t and amplitude φ_0 are derived from angle θ and angular velocity $\dot{\theta}$ of the stance leg, with a given frequency f. As shown in Fig. 4, combinations of angle θ and angular velocity $\dot{\theta}$ can yield different frequencies, thus allowing greater range of desirable hip motion to be possible. The redundancy can be exploited under perturbations: the system can combine different compensation strategies, for example, not only changing step length for stabilization, but also altering the landing timing. This property is useful when the landing place is undesirable (e.g. holes, puddles, fragile objects), or the hip joint angle is close to its limit, or abrupt changes in swing motion would cause the stance leg to lose contact with the ground. Thus, this provides a flexible scheme for the generation of spontaneous motions.

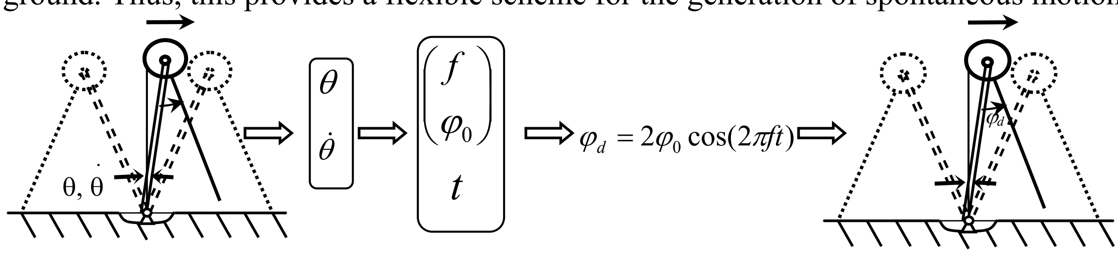

Fig. 5 Scheme for hip joint control in single support phase using the inverse derivation from stance leg states to hip joint parameters, based on the acquired data sets.

4 DISCUSSIONS

We have studied two different relationships for the two support phases of a walking cycle. These relationships show the neutral orbit in phase spaces, and we proposed control strategies that allow sliding within neutral orbits, without following a desirable neutral orbit, or just by following a predefined trajectory in coming up with a controller.

Currently, the implementation of the controller is only applied during the single support phase. In the double support phase, the hip angle controller of the biped was switched off. The hip joint controller to servo is a simple PD (proportional derivative) servo controller.

$$\tau = k_P(\varphi_d - \varphi) + k_D(\dot{\varphi}_d - \dot{\varphi})$$

The desired value of the angular velocity $\dot{\varphi}_d$ is easily derived by the differentiation of the equation of hip joint's desired angle.

In Fig. 6, walking motion was realized only by inertia and only with an arbitrary initial push in the forward direction. During time instance 2.0[s] to 2.1[s], a forward perturbation force of 300[N] was introduced to the upper body. As shown in Fig. 6, the controller was able to compensate with such disturbances.

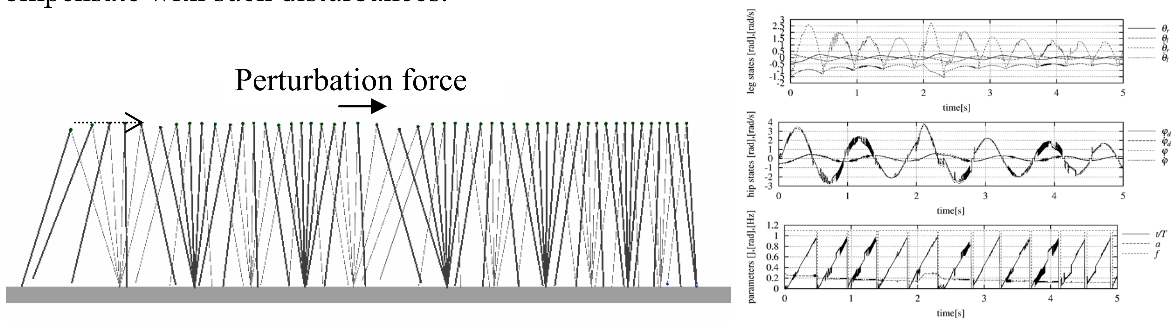

Fig. 6 Stick picture of inertial walking from left to right. Perturbation force was added to walking direction. The time profiles of leg states, hip joint states, and parameters.

In the case of external perturbation the magnitude of 1300[N] was introduced during the time instance 0.25[s] to 0.3[s] as shown in Fig. 7. The biped was pushed backward, and back stepping motion for recovery was generated based on the proposed control method.

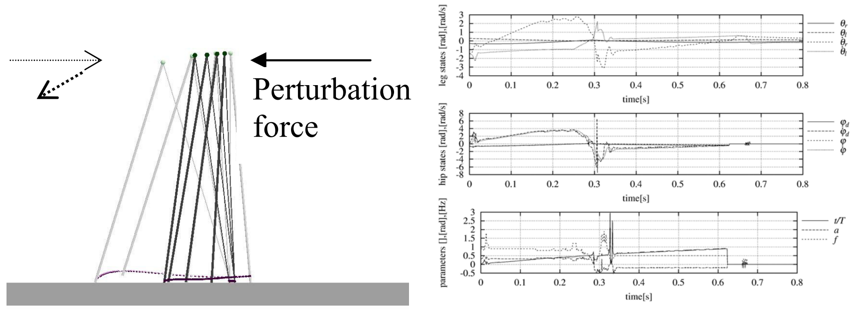

Fig. 7 Stick picture of stepping back caused by perturbation force to backward. The time profiles of leg states, hip joint states, and parameters.

5 CONCLUSIONS

A walking cycle can be divided into two phases, a double support phase, and a single support phase. We derived an empirical equation for the relationship between the step length and initial speed as the desired mechanism for control during the double support phase. We were also able to determine key relationship for the single support phase of walking, utilizing this relationship in producing a biped walker that can generate robust spontaneous motion.

REFERENCES

1. **Hirai, K., Hirose, M., Haikawa, Y.** and **Takenaka, T.** (1998) The Development of Honda Humanoid Robot. In *Proceedings of the International Conference on Robotics and Automation*. IEEE-RAS, pp. 1321–1326.

2. **Ishida, T., Kuroki, Y., Yamaguchi, J., Fujita, M.** and **Doi, T.** (2001) Motion Entertainment by a Small Humanoid Robot Based on OPEN-R. In *Proceedings of the International Conference on Intelligent Robots and Systems*. IEEE-RAS, pp. 1079–1086.

3. **Raibert, M. H.** Legged robots that balance. The MIT Press series of artificial intelligence, The MIT Press, ISBN 0-262-18117-7 1986.

4. **Schwind, W. J.** and **Koditschek, D. E.** (1997) Characterization of monopod equilibrium gaits. In *Proceedings of the International Conference on Robotics and Automation*. IEEE-RAS, pp. 1986–1992.

5. **McGeer, T.** (1990) Passive dynamic walking. In *The International Journal of Robotics Research*. Vol. 9, No. 2, pp. 62–82.

6. **Mochon, S.,** and **McMahon, A.** (1980) Ballistic walking. In *Journal of Biomechanics*. ASB, ISB, ESB and JSCB, Vol. 13, pp. 49–57.

7. **Miyakoshi, S., Cheng, G.,** and **Kuniyoshi, Y.** (2001) Transferring human biped walking function to a machine – Towards the realization of a biped bike –. In *Proceedings of the 4th International Conference on Climbing and Walking Robots (CLAWAR 2001)*. CLAWAR, pp. 763–770.

8. **Morita, S.** and **Ohtsuka, T.** (2002) Gate generation of a compass type biped model on a level surface based on dynamical symmetry. In *Proceedings of the 7th Robotics Symposia*. RSJ, JSME and SICE, pp. 101–106. (Japanese)

9. **Dempster, W. T.** and **Gaughran, G. R. L.** (1965) Properties of body segments based on size and weight. In *American Journal of Anatomy*. pp. 33–54.

10. **Yamazaki, N., Suzuki, T., Kouchi, M., Kusumoto, A.,** and **Nishizawa, T.** Encyclopaedia of foot. The Asakura Shoten, ISBN 4-254-20096-X 1999. (in Japanese)

11. **Goswami, A.** (1999) Postural stability of biped robots and the foot rotation indicator (FRI) point. In *International Journal of Robotics Research*. Vol. 18, No. 6, pp. 523–533.

12. **Miura, H.,** and **Shimoyama, I.** (1983) Control System of Stilts Type Biped Locomotion. In *Journal of Robotics Society of Japan*. RSJ, pp. 176–181. (in Japanese)

13. **Miyakoshi, S.,** and **Cheng, G.** (2002) Ballistic Walking by Compass-like Biped Walker: Exploiting Physical Dynamics in Achieving Human-like Walking. In *Proceedings of the 5th International Conference on Climbing and Walking Robots (CLAWAR 2002)*. CLAWAR, pp. 445–452.