A Bio-inspired Behavior Based Bipedal Locomotion Control – B4LC Method for Bipedal Upslope Walking*

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Though over decades' development of bipedal robots, the terrains that bipedal robots can walk remains limited compared to what human can accomplish. To increase bipedal transversality on upslope terrain, this paper studies the biomechanical and biological aspects of human walking on inclined slopes with underlying the motor skills and reflexive systems. The control strategy can be divided into low and high gradient upslope walking. The strategy for the low gradient uphill walking is generated on the basis of an existing B4LC system. Furthermore, investigating the human walking on high gradient upslope terrain thoroughly unveils a new control strategy for bipedal walking on high gradient slope. Through validating the suggested method on a simulated biped upon different upslope terrains, the bipedal robot shows a naturally looking walking gait, achieving uphill walking up to 15° inclination which can compete with most advanced bipedal robots in the world.

Keywords: biped; B4LC; upslope walking; motor patterns; reflexes

Introduction

Compared to human walking on slope, the bipedal robots possess yet limited walking ability on those terrains. Following we will survey the scientific studies in this area. Chew *et al.*[1] introduced a *Virtual Model Control* approach to a planer bipedal robot for walking over rolling terrain, leading to a rhythmic gait during slope walking. However, the resulting walking looked unnatural and only the sagittal walking was taken into consideration. Huang *et al.*[2] introduced an approach for calculating the future ZMP trajectory for bipedal walking on uneven terrain. Braun *et al.*[3] proposed a state-dependent torque control for a biped in which the inherent dynamics has been fully used. A spring-damper couple is constructed as strictly

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passive functions with fixed equilibrium points. Again, those ZMP-based control methods have many drawbacks as mentioned in.[4,5]

Looking over the mentioned studies on the upslope walking for bipedal robots, the achievement is yet limited. Current research focus only on the modification of ZMP based on the pre-defined trajectories, a more systematic solution for this situation is still missing.

Bio-inspired Control of Upslope Walking for Bipedal Robots

Rather than studying the mathematic model of system dynamics, the bio-inspired control approach absorbs all advantageous aspects of the human body, including its morphology, physiology, muscles, and receptors. The following content will introduce a new approach for walking on upslope based on the suggested B4LC method. Inspired by,[6] Sup *et al.*[7] developed a upslope walking controller for lower limb prosthesis. The knee and ankle kinematic data for healthy subjects walking on level and up 5°, 8°and 10°provide the biomechanical hint for the bipedal robots' upslope walking. Instead of changing the control parameters continuously, Sup *et al.*[7] suggested to insert a finite-state machine to decide the impedance parameters for the lower limb prosthesis in different inclinations. The suggested control approach utilizes the finite-state machine to switch the control parameters and behaviors to accommodate in various inclinations. According to the classification of the suggested controller, the control for upslope walking can be divided into *low gradient controller*, *5° controller*, and *10° controller*. Due to similarities of this *low gradient controller* with the existing B4LC system, we will not study it in this paper.

Slope Walking Controllers

A state machine to switch different controllers based on the detection of the ground inclinations is firstly developed, in which 5°, 10° 15° upslope controllers can be triggered separately.

In walking phase 1 (*Weight Acceptance*), the local reflex *Weight Acceptance Slope* is responsible for stretching knee joint through two strategies. The first one is to keep the current knee angle constantly at the end of the walking phase 5 (*Heel Strike*) until the ipsilateral ankle angle with a dorsiflexion over a threshold value. Then the second one keeps to flex the knee joint till the end of *Weight Acceptance*. Before approaching to a threshold, the distance from the COM to the fore leg becomes relatively longer. Meanwhile, flexing the knee joint leads to rise of the CoM in altitude and requires more propelling power from the rear leg. Therefore, keeping CoM low before the fore ankle approaching to the threshold value θ_{sg} mitigates the forward movement of CoM. Additionally, a second controller stretches the leg by a gradual increase of stimulation. The target knee angle reduces along with a nonlinear speed on the basis of the knee angle at the end of the *Heel Strike*. The postural reflex *Forward Velocity Slope* generates torque at ankle joint in accordance with the CoM error. In walking on the high gradient slope, due to the gravitational potential and disturbances, *Forward Velocity Slope* is formulated as a PD-controller to stabilize the ankle joint. The target angle of the ankle $\alpha_{ankley,target}$ in the 10° indicates the desired dorsiflexion angle of the stance leg, as listed in Table 1. In the slope locomotion, the oscilla-

Table 1. The target ankle angle of *Forward Velocity Slope* in different controllers.

Controller	The target ankle angle (deg)
10° uphill controller	$5 + \frac{1}{2}\theta_{sg}$
15° uphill controller	$10 + \frac{1}{2}\theta_{sg}$

tion in the lateral direction becomes more disturbing. The development of posture reflexes for lateral stability, which mainly inherit the behaviors of original ones with slight modification, overwhelm this unexpected behavior.

In the walking phase 2 (*Propulsion*), two posture reflexes, *Upright Trunk Slope* and *Lateral Balance Ankle Slope* and two local reflexes, *Stabilize Pelvis* and *Forward Velocity Slope* keep active as in *Weight Acceptance*. Two new control units, motor pattern *Ankle Propel Slope* and the local reflex *Knee Propel Slope*, are developed to generate torques to propel the rear leg moving upwards and forwards.

Stretching the knee with an acceleration by the *Knee Propel Slope* results in facilitating the forward movement and lowering the CoM vertically at the same time. The stretching speed is proportional to current knee angle error, as described in Table 2. Stretching too fast at the beginning will result in an enormous upward kinetic energy acting on the body trunk, generating even a jump motion. Hence, the knee stretching starts with a relative low angular velocity to avoid this behavior. The motor pattern *Ankle Propel Slope* is only active after the contralateral leg touching on the ground. The *Ankle Propel Slope* inherits the algorithm mentioned in.[4] The distinction is, beside the desired velocity, the $xcom_{for.vel.,error}$ and the slope gradient,

Table 2. The knee angle error and corresponding speed in *Knee Propel Slope*

Difference between current and reference	Stretching speed
$difference > \frac{7}{8} reference\ angle$	$1 \cdot \dot{\alpha}_{knee\_stretching}$
$difference > \frac{5}{8} reference\ angle$	$4 \cdot \dot{\alpha}_{knee\_stretching}$
else	$8 \cdot \dot{\alpha}_{knee\_stretching}$

the $xcom_{for.vel.,error}$ of the opposite body side are introduced to generate a compensating torque working as an assistant propulsion during the dorsiflexion of the contralateral ankle.

Among all active control units in the walking phase 3 (*Stabilization*), *Upright Trunk Slope*, *Lateral Balance Ankle Slope*, *Stabilize Pelvis* and *Ankle Propel Slope* continue working as in previous phase. The slope gradient signal θ_{sg} is passed to the *Initialize Swing Slope* as a modulation signal to generate an additional torque in order to increase the swing velocity. The reasons for increasing the swing velocity can be summarized as following: First, in the slope locomotion mode, the knee angle at heel strike flexes more than that in walking on the level ground, leading to decrease the step length from the ipsilateral leg nearly 50 percent since the shank has the similar length as the thigh. To keep the step length long enough for both leg during this motion, the hip should stop swinging at the end of swinging behavior with a larger attack angle due to increased swinging speed. Second, in the swinging process, the perpendicular distance from the point of hip joint to the slope surface decreases with the ankle dorsiflexion of the supporting leg. Increasing the swinging velocity makes the foot of the swing leg pass the 'foot clearance' earlier and dwindles the possibility of the swinging leg hitting the ground.

In walking phase 4 (*Leg Swing*), the hip joint in the swinging process is controlled by the local reflex *Lock Hip Slope* until the leg comes to a swinging stop and touching down on the ground. This is a position control adjusting the hip angle through estimating the step length.

Compared to walking on level ground, the step length in the slope locomotion decreases with the dorsiflexion of the knee joint at the heel strike by reducing the required propelling torque. However, shorter step length could result in leaning forward seriously of the trunk. The calculation of target step length can be separated into two parts: the step length offered by the fore leg S_{fore} and by the rear leg S_{rear}. To implement this strategy, two prerequisite are needed: first, the rear leg is fully stretched; second, the shank of the fore leg is perpendicular to the level ground. The S_{rear} can be formulated by the parameters of the rear leg, as described in Eq. (1).

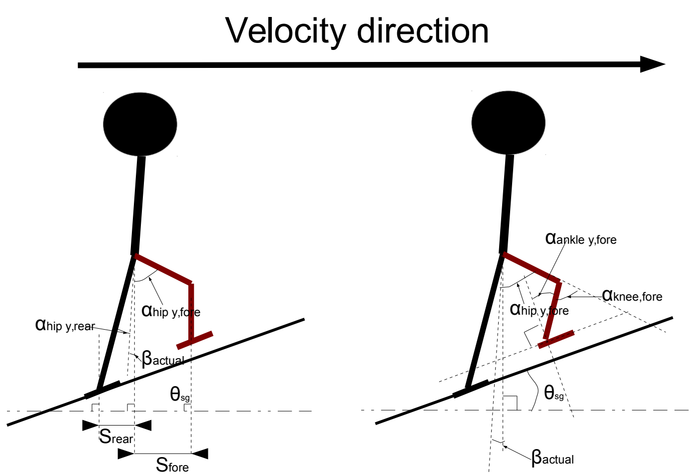

Fig. 1. The relevant parameters for the estimation of step length (left) and the geometry of target ankle angle in walking phase 4 (right).

$$S_{rear} = \sin(\alpha_{hip\ y,rear} + \beta_{actual}) \cdot (l_{thigh} + l_{shank}) \tag{1}$$

Where, $\alpha_{hip\ y,rear}$ indicates the current rear hip angle, l_{thigh} and l_{shank} denote the length of the thigh and shank, respectively. Then the S_{fore} can be estimated by the Eq. (2)

$$S_{fore,est} = \sin(\alpha_{hip\ y,fore} - \beta_{actual}) \cdot l_{thigh} \tag{2}$$

And the total step length $S_{estimation}$ equals the sum of the $S_{fore,est}$ and S_{rear}. When the difference between $S_{estimation}$ and S_{target} is larger than a threshold and is inversely proportional to the slope gradient, the position control of the *Lock Hip Slope* will take the geometrical hip angle as the target hip angle to avoid emergence of short step length. The geometrical hip angle is formulated by the Eq. (3).

$$\alpha_{hip\ y,fore} = \arcsin\frac{S_{fore,target}}{l_{thigh}} + \beta_{actual} \tag{3}$$

Where,

$$S_{fore,target} = S_{target} - S_{rear} \tag{4}$$

For the walking on the slope , on account of the rise of the ground, the local reflex *Lock Knee Slope* acts as an active position controller to reduce the forward step length of the swinging leg at the beginning. After the swing leg passes the 'foot clearance', *Lock Knee Slope* starts to stretch the swing leg to the target knee angle with increasing activation gradually. On the basis of the kinematics analysis on the inclined walkway, the target knee angle at the heel strike is set as shown in Table 3.

Table 3. The target knee angle at heel strike in different controllers

Controller	The target knee angle at heel Strike(deg)
10° uphill controller	$2.5 \cdot \theta_{sg}$
15° uphill controller	$5 + 2 \cdot \theta_{sg}$

In the slope locomotion mode, a cutaneous reflex *Ankle Swing Slope* is introduced. Through the position control, this reflex keeps the foot parallel with the ground surface during the whole walking phase 4 to reduce the forward step length. The target ankle angle $\alpha_{target\ ankle\ y,fore}$ is calculated as in the Eq. (5).

$$\alpha_{target\ ankle\ y,fore} = 90^\circ + \alpha_{hip\ y,fore} - \alpha_{knee,fore} - \beta_{actual} - \theta_{sg} \quad (5)$$

In walking phase 5 (*Heel Strike*), the posture reflex *Lateral Foot Placement Slope* and the local reflex *Lock Hip Slope* continues functioning. The posture reflex *Weight Acceptance Slope* described in the *Weight Acceptance* takes the charge of the knee control from the *Lock Knee Slope*. Before touching the ground of the foot, the knee joint increases the stiffness in order to keep the angle during foot landing. The local reflex *Heel Strike* starts regulating ankle dorsiflexion immediately after touching ground.

Experimental Results

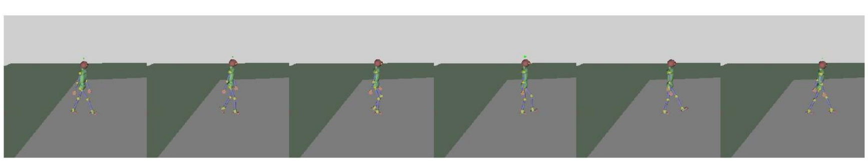

Fig. 2. A part of the stride of the simulated biped walking on the 5° upslope

To validate the suggested control methods and evaluate their performance, a simulated bipedal robot with 21 degrees of freedom and the height up to 1.8 m (see Fig. 2) has conducted specific walking tasks on different slopes.[4] The experiments are conducting the bipedal walking on upslope at 8°, 10° and 15° respectively.

As can be seen in the left figure of Fig. 3, the main difference of the knee trajectories is that the maximum knee flexion during the swing phase decreases from 62° on level ground to 60° at 5° inclination. Due to the component of the gravitational force parallel to the slope, the rear leg supports more weight during stabilization phase, incurring a slower hip and knee flexion after toe off. The plantarflexion of the ankle joint increases from 22° on level ground to the 30° at 5° inclination which reflects the leaning forward of the whole body before propulsion.

The angle trajectories of the simulation results for walking on the 8°, 10° and 15° upslope are illustrated in the right figure of Fig. 3. The knee flexion during the heel strike phase among various slopes show significant differences. It increases from 4.5° to 38° along with an increase in upslope's inclination from 0° to 15°. This is induced by the local reflex *Lock Knee Slope* and shortened step length. Meanwhile, the shorter step length requires a smaller plantarflexion of the ankle joint before toe off.

As illustrated in Fig. 3, hip trajectories show a similar behavior as that of knee joint. The main difference is that walking on steeper upslope requires more hip flexion during heel strike and weight acceptance.

Considering the kinematics of ankle joint, one can find that ankle joints rotates for both plantarflexion and dorsiflexion in a smaller range when the upslope inclination increases. This is because in upslope walking, it requires faster propulsion and shorter duration in weight acceptance, resulting in avoidance of leaning forwards or backwards of the COM of the biped.

Conclusion

Inspired by studying the kinematics of human walking on those slopes, we have developed specific motor patterns and reflexes to implement varying upslope walking up to 15° in this paper. For future work, including systematical descriptions for both the motor patterns and reflexes during changing upslope and velocities, this way, can facilitate the introduction of optimization and learning schemes into the B4LC system, thus it leads to emergence of more human-like and efficient walking behaviors.

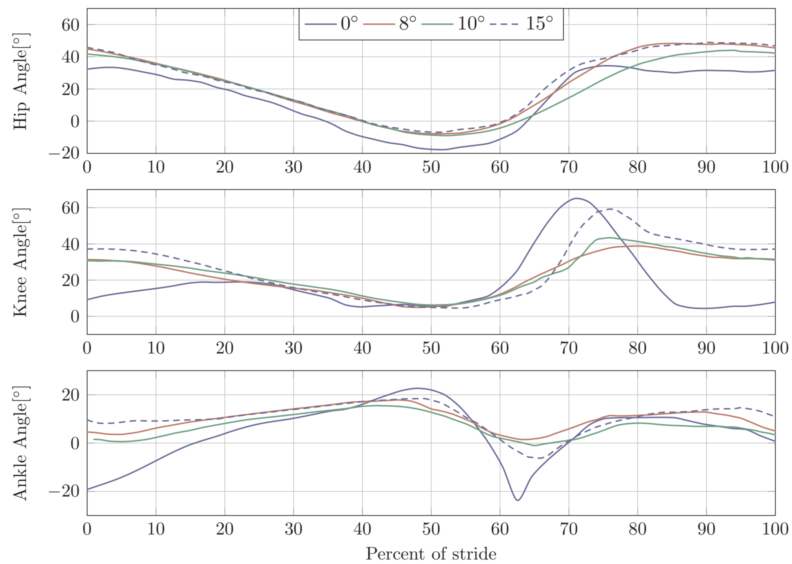

Fig. 3. The trajectories of the hip, knee and ankle joints among bipedal walking on level ground, 8°, 10° and 15° upslope. HS, CTO, CHS and TO indicate heel strike, contrateral toe off, contralateral heel strike , and toe off individually.

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