Slipping and Tripping Reflexes for Bipedal Robots

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Abstract— **Many robot applications require legged robots to traverse rough or unmodeled terrain. This paper explores strategies that would enable legged robots to respond to two common types of surface contact error: slipping and tripping. Because of the rapid response required and the difficulty of sensing uneven terrain, we propose a set of reflexes that would permit the robot to react without modeling or analyzing the error condition in detail. These reflexive responses allow robust recovery from a variety of contact errors. We present simulation trials for single-slip tasks with varying coefficients of friction and single-trip tasks with varying obstacle heights.**

Keywords— **reactive control, reflexes, rough terrain, slipping, tripping, biped locomotion**

I. Introduction

ROUGH terrain occurs not only in natural environments but also in environments that have been constructed or modified for human use. Currently, most legged robots lack the control techniques that would allow them to behave robustly on such relatively simple rough terrain as stairs, curbs, grass, and slopes. Even smooth terrain becomes difficult to traverse if it includes small obstacles, loose particles, and slippery areas. Many control systems for bipedal robots have assumed steady-state running over smooth surfaces, but some have explored control techniques for rough terrain. Statically stable robots, which always maintain their balance over at least three legs, have used controllers with foot-placement algorithms to insure viable footholds. However, for dynamically stable robots, which run with a ballistic flight phase, constraints on timing and foot placement increase the difficulty of designing controllers that can anticipate rough terrain or react to errors. This paper demonstrates the effectiveness of preprogrammed high-level responses to errors during locomotion in a complex dynamic environment. A suite of responses allows a simulated, three-dimensional, bipedal robot to recover from slipping on low friction surfaces and tripping over small obstacles (Figure 1).

Many ground contact errors would be avoided if the control system could guide the robot around slippery areas and obstacles. However, the approximate nature of sensor information obtained at a distance means that it is not always possible to sense the surface properties of terrain before making contact. For example, small holes, bumps, debris, and sticky or slippery areas are difficult to detect from a distance with current technology. If the robot cannot detect and avoid or prepare for surface features in advance, then robust locomotion on rough terrain requires that the robot respond to unexpected features after the contact error has occured and before the robot crashes. For dynamically stable robots, the time available for modeling the surface and planning an appropriate reaction is severely limited. In the case of the dynamically stable bipedal robot shown in Figure 2, the controller may have less than a few hundredths of a second in which to choose or plan an appropriate recovery.

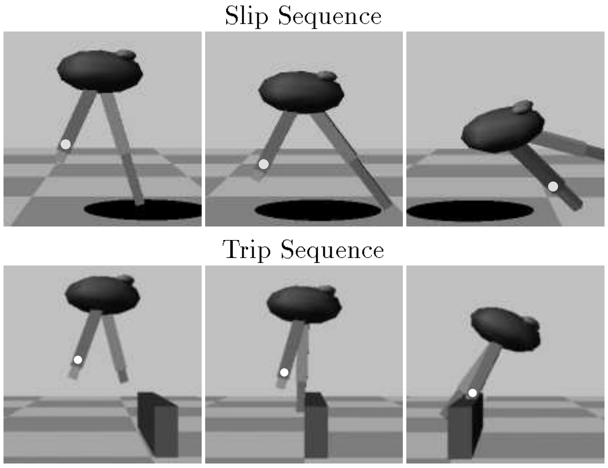

Fig. 1. **Examples of a Slip and Trip.** Without the addition of reflexes for recovering from slips and trips, the simulated robot does not respond successfully to slippery areas or contact with an obstacle.

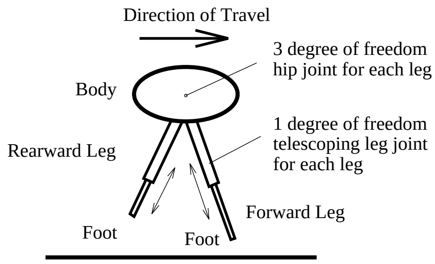

Fig. 2. **Biped Structure.** The simulated bipedal robot consists of a body and two telescoping legs. Each leg has three degrees of freedom at the hip and a fourth degree of freedom for the length of the leg.

We define *reflexes* as responses with limited sensing and no explicit modeling. That is, the robot can detect a slip or a trip, but makes no attempt to estimate the properties of the surface or obstacle or to calculate a corresponding recovery plan. Instead, the slipping and tripping sensors trigger fixed responses. These reflexes are defined at a high level, such as reconfigurations of the leg positions, and at a low level, such as modifications of servo gains. Just as animal motor programs can be considered both open-loop and closed-loop[1], several low-level feedback control laws operate during the primarily open-loop reflex responses. For example, a reflex may reconfigure the leg position, but sensing is used to determine transitions in the leg controller state machine during the recovery step.

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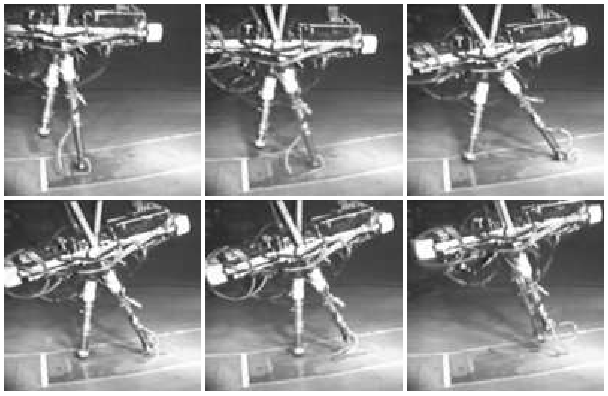

Fig. 3. **Physical Biped Slip.** Planar two-legged robot running across an oily spot on the floor. Footage from the MIT Leg Laboratory. [Frames: 0, 35, 70, 91, 105, 140]

During experimentation with a physical, planar biped, the robot sometimes slipped on hydraulic oil or tripped on cables in its path. Because the robot had no responses customized for these error conditions, it almost always immediately crashed. This paper reports a set of fixed reflexes that enable robust recoveries for a simulated three-dimensional robot in tasks involving a single slip or trip.

In the next section, we describe previous approaches to legged locomotion in rough terrain. In Section III, we consider biological reflexes. Section IV describes the simulated bipedal robot and its control system. The slipping problem, slipping reflexes, and simulation results are presented in Section V, followed by the tripping problem, tripping reflexes, and results in Section VI. The reflex approach and results are discussed in Section VII.

II. Locomotion on Rough Terrain

A suitable foothold is one that allows a legged system to maintain balance and continue walking or running. For statically stable locomotion, the difficulty is not in placing the robot's feet on footholds, but in deciding which locations on the terrain provide suitable footholds. Successful locomotion on rough terrain was demonstrated by the Adaptive Suspension Vehicle[2] and by the Ambler[3], [4], [5]. These large, statically stable machines traversed grassy slopes, muddy cornfields, and surfaces that included railroad ties and large rocks. Static stability allowed these robots to emphasize detection at a distance and avoidance of obstacles and uncertain footholds.

Klein and Kittivatcharapong[6] proposed algorithms for insuring that foot forces remain within the friction cone and identifying situations in which these constraints, or the desired body forces and torques, could not be achieved. Their work addressed prevention of slipping and did not consider sensor noise or responses to unmodeled surfaces.

For dynamically stable robots, the control of step length for locomotion on rough terrain interacts with the control of balance. Hodgins and Raibert[7] implemented three methods for controlling step length of a running bipedal robot. Each method adjusted one parameter of the running cycle: forward running speed, running height, or duration of ground contact. In laboratory demonstrations, a biped running machine used these methods for adjusting step length to place its feet on targets, leap over obstacles, and run up and down a short flight of stairs. However, unlike the tasks described below, the size and location of the objects were known to the controller in advance.

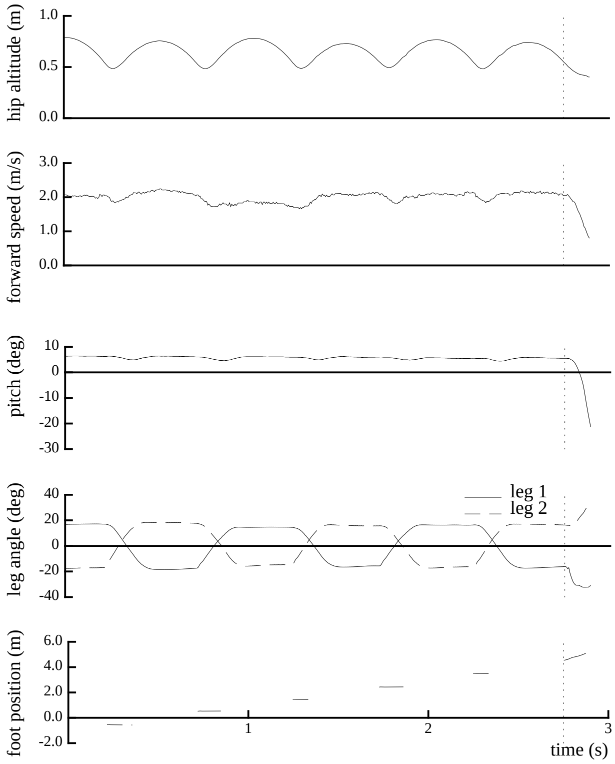

Fig. 4. **Slipping Data of the Physical Robot.** The physical planar robot slipped on oil during a laboratory experiment at the point indicated by the vertical dotted lines. The top three graphs show the height, forward speed, and orientation of the body. The bottom two graphs show the angles of each leg and the position of each foot on the ground. For each step but the last, the foot is stationary while it is on the ground.

Nagle[8] developed algorithms for running on terrain that was known to be slippery. By running slowly, the robot generated nearly vertical foot forces. His controller used *a priori* knowledge or estimation of friction coefficients to prevent slipping by confining control forces and torques to slip-free regions.

Kajita and Tani[9] used an ultrasonics sensor to construct a ground profile of terrain that consisted of horizontal surfaces at varying heights. Yamaguchi *et al* have built a bipedal robot that uses feet to sense ground inclinations and plan appropriately[10], although it was not able to react to slips or trips.

III. Reflexive Responses to Errors

Biological systems use many different reflexes in locomotion and manipulation. Reflexes help to restore balance when perturbations occur during walking or standing[11], [12], [13]. The role of reflexes in walking is complex: the same stimulus elicits a different response in the stance phase than in the swing phase[14], [15], [16]. Touching the foot of a cat or human during a swing phase, for example, will cause the leg to flex, raising the foot. If an obstacle caused the stimulus, this response might lift the foot over the obstacle and allow walking to continue. During the stance phase, a stimulus delivered to the foot causes the leg to push down harder, resulting in a shorter stance phase. Although these actions are opposite, both facilitate the continuation of locomotion.

Robotics has adopted the term "reflex" from the biological literature, but in both biology and robotics the precise definition of the term varies from study to study. Most researchers in robotics use the term to mean a quick response initiated by sensory input. Some require reflexes to be open-loop and to proceed independently of subsequent sensory input[17], [18]; others apply the term more loosely to describe actions that are performed with feedback until a terminating sensory event occurs[19]. In some cases, reflexes refer to general purpose actions[20], [21] and in others only to actions taken to correct errors or to compensate for disturbances[19] or transitions[22].

Brooks's subsumption architecture[21] combined several simple reflex-like actions to produce complex behaviors such as six-legged walking. A global gait generator specified the order of leg use while inhibitory connections between the legs prevented conflicting reflexes from acting simultaneously. Other hexapod robot researchers have designed subsumption controllers for rough terrain[23] and have integrated reactive leg control with gait planning for rough terrain[24].

Hirose[20] built and controlled a statically stable quadruped that used a reflexive probing action to climb over objects and to walk up and down steps without visual input or a map of the terrain.

Wong and Orin[19] implemented two reflex responses for a prototype leg of the Adaptive Suspension Vehicle. Using velocity and hydraulic pressure information from sensors at the joints, they were able to detect foot contact and slippage. A foot contact reflex reduced the peak forces at touchdown. A foot slippage reflex was used to detect and halt slipping.

Reflex responses have also been used in manipulation. Tomovic and Boni[17] used a reflex response to implement grasping for the Belgrade prosthetic hand. Bekey and Tomovic[18] continued the exploration of prosthetic control systems with a rule-based technique that relied on sensory data and fixed response patterns.

IV. Dynamic Bipedal Robots

The simulated robot used in our research is based on a planar bipedal robot constructed by Raibert and colleagues[25], [26]. The simulated robot is three-dimensional and has three controlled degrees of freedom at each hip and one for the length of each leg (Figure 2). In the physical robot, the leg contains a hydraulic actuator in series with an air spring. The simulation models the spring and actuator as a linear spring with a controllable rest length. In

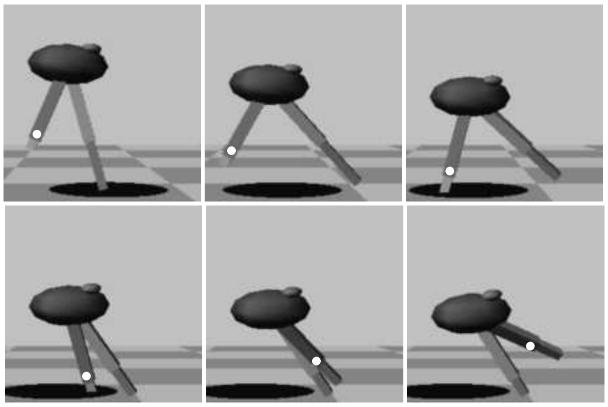

Fig. 5. **Simulated Biped Slip.** The dark circle represents an area of the floor with a reduced coefficient of friction. Without slipping reflexes, the simulated robot is unable to complete a step on a slippery surface. The first leg slips, almost immediately becoming airborne as it accelerates forward. As the body falls, the second leg hits the surface and also slips. The second leg continues to accelerate forward. [Friction coefficient: 0.04. Times (s): 0.0, 0.06, 0.09, 0.11, 0.12, 0.13]

experiments with the physical robots, hydraulic fluid occasionally created slippery spots that caused the robot to fall (Figures 3 and 4). A simulation of a similar fall is plotted in Figures 5 and 6. The physical robot was also able to climb stairs and jump over boxes[26]; however, the positions of the obstacles were known in advance. The current research extends the controller to handle unexpected slips and unanticipated collisions with a box.

The controller achieves dynamically stable, steady-state running by decomposing the control problem into three largely decoupled subtasks: hopping height, forward velocity, and body attitude. Hopping height is maintained by adding enough energy to the spring in the leg during stance to account for the system's dissipative losses. Forward velocity is maintained by choosing a leg angle at touchdown that provides symmetric deceleration and acceleration as the leg compresses and extends. The attitude of the body (pitch, roll, and yaw) is maintained with proportional-derivative servos that apply torques between the body and the leg while the foot is on the ground.

The robot control system is implemented as a state machine that sequences through the flight and stance phases for each leg, applying the control laws that are appropriate for each state. As shown in Figure 7, *flight* is followed by a stance phase of four states. During *loading*, the foot makes contact with the ground and begins to bear the weight of the robot. During *compression*, the leg spring is compressed by the downward velocity of the robot. After the spring has stopped the vertical deceleration of the body, the body begins to rebound during *thrust*. As the leg reaches maximum extension during *unloading*, it ceases to bear weight. After liftoff, the roles of the legs are reversed and the second leg is positioned forward in anticipation of touchdown. For further details on the control system, see [26] and [25].

The control system's state machine depends on measurements of leg length to determine state transitions dur-

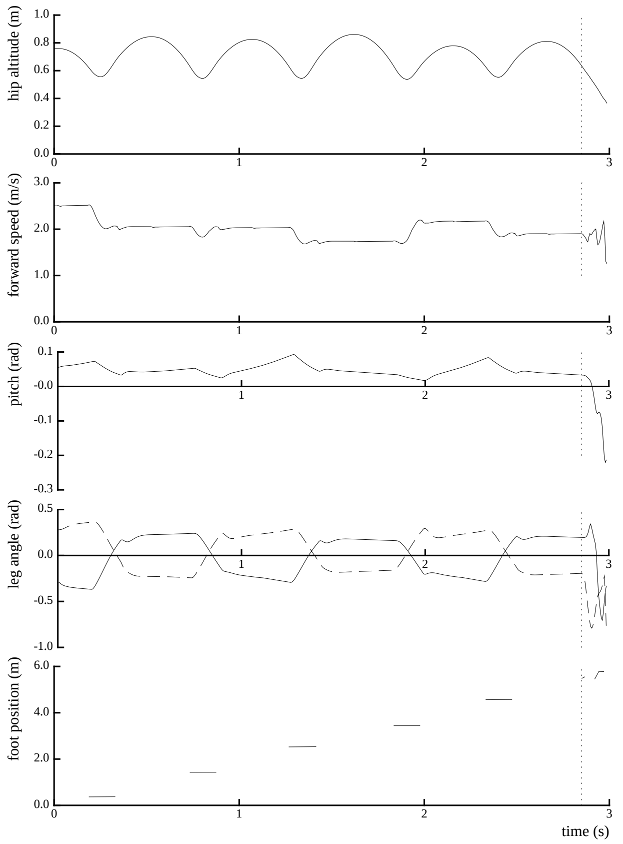

Fig. 6. **Slipping Data of the Simulated Robot.** After taking five steps on a surface with a friction coefficient of 1.0, the simulated robot steps on a region with a coefficient of 0.20 and slips. Because no slipping recovery strategies are active, the robot falls. The top three graphs show the height, forward speed, and orientation of the body. The bottom two graphs show the leg angles of both legs and the position of each foot on the ground. When the foot slips (vertical dotted line), it leaves the ground and the other foot soon impacts.

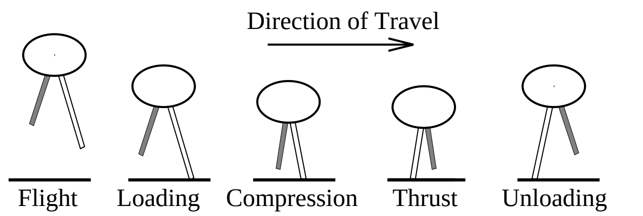

Fig. 7. **Control States.** Running is achieved by dividing each step into several states and applying the appropriate control laws during each part of the running step.

ing steps. Slips may interfere with control by altering leg lengths unexpectedly. The transition from loading to compression, for example, occurs when the leg has shortened by a small amount. After a slip, the leg may lengthen. Not only must slipping reactions prevent these errors, but they must minimize interference with normal control, such as the adjustment of body attitude.

V. Slipping

The impact of the foot on the ground, the weight of the robot, and the forces and torques generated by the hip and leg servos create a force on the ground during a step (Figure 8). Slipping occurs when the horizontal component of the force of the foot on the ground, F_h, exceeds the maximum force of static friction generated by the ground. A simple model of this interaction is that the maximum force of static friction is directly proportional to the normal force of the ground on the foot, F_v. Under this model, slipping will occur when the horizontal component of F exceeds the vertical component times the coefficient of static friction:

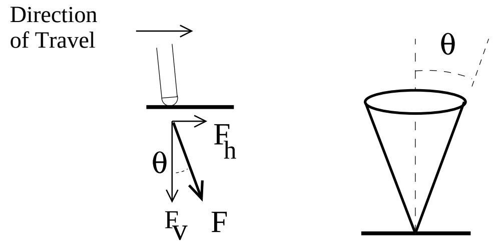

Fig. 8. **Foot Forces and the Friction Cone.** During a step, the foot produces forces on the ground, F, with horizontal and vertical components, F_h and F_v. Slipping occurs when the angle of the impact force is outside the friction cone.

$$F_h > \mu_s F_v,$$

where μ_s is the coefficient of static friction. When slipping occurs, the horizontal force returned by the ground is given by

$$F_h = \pm \mu_d F_v,$$

where μ_d is the coefficient of dynamic friction and the sign of F_h should remain unchanged. These relationships define a *friction cone*, illustrated in Figure 8. When the force of the foot on the ground lies within the friction cone, the foot does not slip. The angle of the cone is given by

$$\theta_{max} = \tan^{-1} \mu_s.$$

Note that this cone is defined for foot forces, not leg angles. The motion of the leg prior to impact affects the direction of the foot's force on the ground, as do the control torques applied to the hip joint and the leg spring. Foot forces are most likely to exceed the friction cone at the beginning or end of a step, when the angle of the force vector is greatest. Slips at the beginning of a step are more likely than slips at liftoff because the foot is moving with respect to the ground at touchdown. In contrast, the foot is stationary at liftoff. Slips during liftoff are often less critical because the step is nearly complete; the controller has already executed corrections during the step.

Our simulations assumed minimal sensory information: the properties of the surface and the extent of the slipping area were not available to the control system. The controller could not adjust the leg configuration prior to touchdown or try to position the foot outside the slippery area to find a secure foothold. Neither the forces on the feet nor the coefficients of friction were available to the control system. However, the control system could detect slips. In the simulation, slips were detected when a foot moved while in contact with the ground. The control system of a

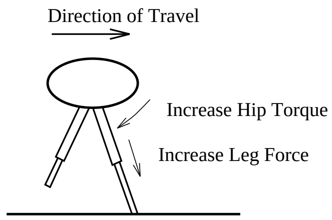

Fig. 9. **Same-Step Reactions.** When a slip has been detected, a torque can be applied at the hip to reduce the horizontal force on the ground or the leg can be extended to increase the vertical force.

physical robot can detect slips indirectly by measuring joint angles and velocities or structural forces. Direct methods include encoder wheels and micro-slip detectors.

When the control system has detected a slip, it can attempt to continue the step or abandon that step and pull the leg off the ground. In the first case, hip torques or leg forces can be applied to increase the vertical component of the foot force while decreasing the horizontal component, thus returning the force vector to within the friction cone. If the step is abandoned, one of the legs can be positioned during the next flight phase so that the leg angle at the next touchdown will be near vertical or both legs can be moved to a triangular configuration. In the simulations described here, we defined a response to be successful if the robot was able to continue running after slipping and taking a recovery step in the slippery region, then taking subsequent steps on a non-slippery surface. Changes in velocity or hopping height were not considered failures provided that the control system was able to maintain balance and return to steady-state running.

A. Same-Step Response Strategies

Reacting to a slip requires careful management of the horizontal and vertical components of the forces generated by the impact of the foot on the ground. Initial responses to a slip can attempt to alter the force vector immediately by generating a torque at the hip or a force axial to the leg (Figure 9).

The first reaction responds to a slip by increasing the hip torque by a fixed amount. In most cases, this action increases the vertical component of the foot's force on the ground. After the foot stops slipping, the hip controller reverts to its normal task of correcting pitch errors. This strategy may have undesirable consequences because a torque applied at the hip also increases the forward velocity of the body thus increasing the likelihood of a slip on a subsequent step. Applying a torque at the hip also interferes with the correction of body attitude during stance and tends to increase the pitch of the body.

The second reaction responds to a slip by compressing the leg spring a fixed amount to increase the vertical force at the foot and regain a foothold. In a normal running step, the leg spring stores energy during the stance phase and causes the body mass to have approximately equal and opposite vertical velocities at liftoff and touchdown. To maintain the duration of flight, the control system lengthens the leg to add energy equivalent to that lost due to internal mechanical losses and to the impact of the unsprung mass of the lower leg with the ground. In a normal step, thrust occurs at the moment of maximum compression of the spring (Figure 10). In responding to a slip, the control system may alter this sequence by extending the leg as soon as the slip is detected. If the leg is close to vertical, this extension increases the vertical component of the foot's force on the ground and may stop the slip. The extension also adds energy into the leg spring. The extra energy is removed later in the step by lengthening the leg spring when the leg is vertical, leaving the hopping height unchanged (Figure 10).

One effect of this reaction is to slow the robot, a de-

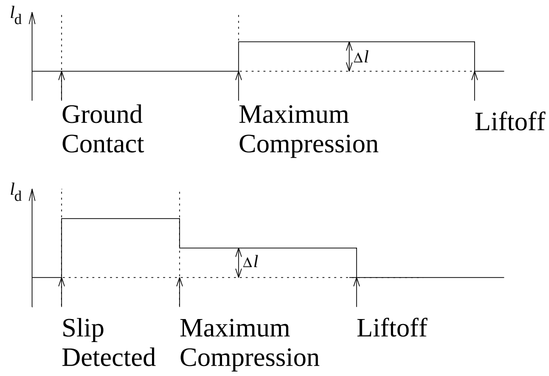

Fig. 10. **Forcing the Foot into the Ground.** In a normal step (top), energy is added into the leg spring at the moment of maximum compression. In the forced step (bottom), the loading on the leg is increased just after touchdown, forcing the foot into the ground and shortening the step duration. l_d is the desired leg length. Δl is the change in desired leg length that returns the robot to the desired hopping height.

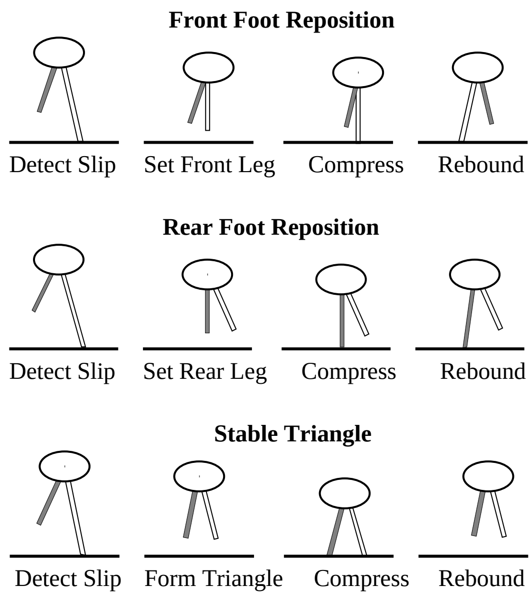

Fig. 11. **Repositioning Strategies.** After a slip has been detected, the initial step is abandoned and one or both legs are repositioned for the next step. The leg angle at touchdown on the next step will be closer to vertical, keeping the impact force vector within the friction cone.

sirable effect when the surface is slippery. However, the foot forcing reflex may lead to a crash if the leg geometry and velocity is such that extending the leg increases the horizontal forces on the foot more than the vertical forces. Thus, the foot forcing reflex may not be sufficient in itself to recover from slips.

The foot forcing reaction shortens the period of time during which the spring is passively compressed, leading to a shorter stance phase and a style of running that utilizes quick hops rather than long strides. We have observed that this quick-stepping behavior is a useful method for running briefly on slippery surfaces because the leg angle at touchdown is near vertical. However, the shorter stance phase also reduces the available time for correcting the body attitude and makes steady-state running difficult to achieve.

B. Repositioning Strategies

The step on which the initial slip occured may be abandoned by immediately lifting the foot; the resulting flight phase provides a brief opportunity to prepare for another landing on the slippery surface. By reconfiguring the legs during the flight phase following the initial slip, the control system can attempt to keep the foot forces within the friction cone. Because the coefficient of friction is not known, the size of the friction cone is unknown. Therefore, the best place for the foot at the next touchdown is directly under the body, making the leg vertical at touchdown. Figure 11 diagrams the strategies that reposition the legs. Figures 12, 13, and 14, contain sequences showing the repositioning strategies involved in recovering from a slip.

After a slip has been detected, both legs may be used in the recovery by configuring them in a narrow fixed triangle vertically centered under the body. The control system attempts to hold this triangle throughout the subsequent step and does not apply the normal pitch, roll, and yaw adjustments. Instead, the robot bounces, letting the geometric configuration provide stability rather than using active control. The leg angles in normal running are nearly symmetric during the flight phase of steady-state running; the control system only has to equalize the leg lengths to create a symmetric triangle. Because the extent of the friction cone is unknown, the triangle is narrowed so the legs are close to vertical. When both feet contact the ground, foot forcing is applied to each to reduce the time of stance. After both feet have lifted off the ground, the control returns to a normal flight state.

C. Slipping Results

The slipping strategies were tested in simulation by varying the initial velocity of the robot and the coefficient of friction to produce multiple runs. For each trial, a circular slippery area was simulated at the location of the first footfall. During successful runs, the robot stepped once in the slippery area and then five additional times on a non-slippery surface. The initial velocity was 2.5 ± 0.25 m/s. The size of the slippery area for each reaction strategy was large enough to prevent a foot from sliding to the edge, a situation that allowed an easy recovery. The slippery area was small enough that subsequent footfalls were located outside of it. Twenty friction coefficients between 0.025 and 0.5 were used. Both static and dynamic coefficients were set to the same value for each trial of 20 simulations with different initial velocities. The robot was judged able to recover from a slip at a given coefficient of friction if at least half of the trials were completed successfully.

For the successful trials, we computed a measure of the error at touchdown of the step after the recovery step that followed the slip. The error measure was the summed absolute values of differences between the actual and desired angles for the body yaw, α, pitch, β, and roll, γ:

$$\text{Error} = |\alpha - \alpha_d| + |\beta - \beta_d| + |\gamma - \gamma_d|\,.$$

The error calculation was designed to measure how well the slip recovery strategy had positioned the robot after the slip step, the recovery step, and the subsequent ballistic flight. The errors for the successful trials were averaged to compute the data shown in Figure 15. This graph illustrates the tradeoff between the two types of strategies.

With no active reflexes, the controller is able to negotiate friction coefficients as low as 0.28. Upon contact, the foot slides; as it is loaded, the vertical and horizontal forces increase, pushing the foot back under the body. Eventually the forces on the foot reenter the friction cone, slipping ceases, and a normal step ensues. The foot forcing strategy causes the foot to slide further out from under the body, leading to fewer recoveries at lower coefficients of friction than the steady-state control system. We observed this effect for several running speeds and heights. However, it may be a consequence of the geometry of the robot design; foot forcing may be useful for slow moving robots or those with other gait patterns. The hip torque reflex succeeds at pulling the leg back and enables recoveries as low as 0.22. Note that hip torque does indeed increase the body pitch, producing increased errors shown in the graph.

The repositioning strategies delay error correction while the legs are reconfigured. As a result, the repositioning strategies produce larger errors upon return to normal running than the foot forcing and hip torque reflexes. However, the repositioning strategies are able to recover from slips on surfaces with smaller coefficients of friction. By lifting the leg and repositioning it within the friction cone, the front and rear repositioning reflexes are able to recover from surfaces with coefficients as low as 0.07 and 0.15, respectively. The front repositioning strategy is more successful than the rear repositioning strategy because it more effectively reduces the relative speed of the foot over the ground before impact. Because the robot is moving forward while the foot is airborne, bringing the rear leg forward increases the relative speed between the foot and the ground. The front repositioning strategy brings the front leg back, reducing the relative speed. On impact, the foot with the lower relative speed is subjected to smaller horizontal forces and is less likely to slip.

The robot experiences increased slipping as the coefficient of friction decreases, but it often recovers because

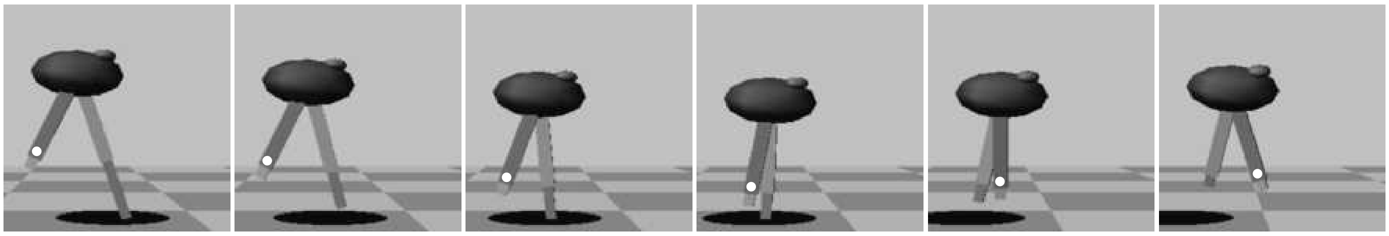

Fig. 12. **Front Leg Repositioning.** The front leg is lifted and repositioned for a more vertical impact. [Friction coefficient: 0.20. Times (s): 0.0, 0.02, 0.05, 0.07, 0.12, 0.15]

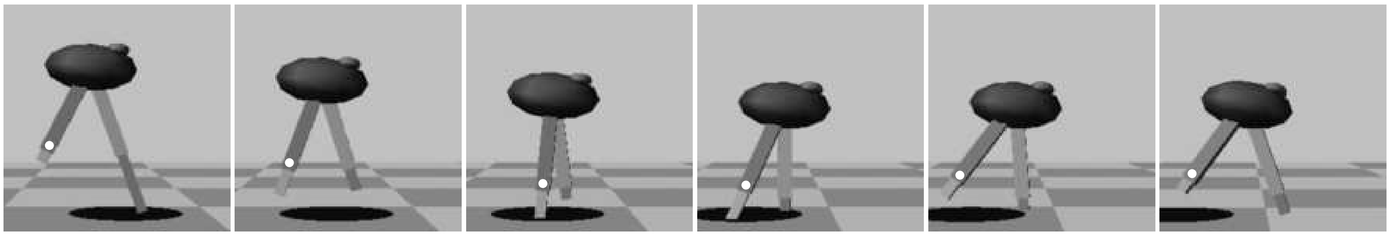

Fig. 13. **Rear Leg Repositioning.** The rear leg is brought under the slipping robot to arrest the fall. The newly planted leg slips upon takeoff, but the step is successful because the body attitude is not disturbed significantly. The robot is able to continue running. [Friction coefficient: 0.20. Time (s): 0.0, 0.04, 0.07, 0.12, 0.13, 0.16]

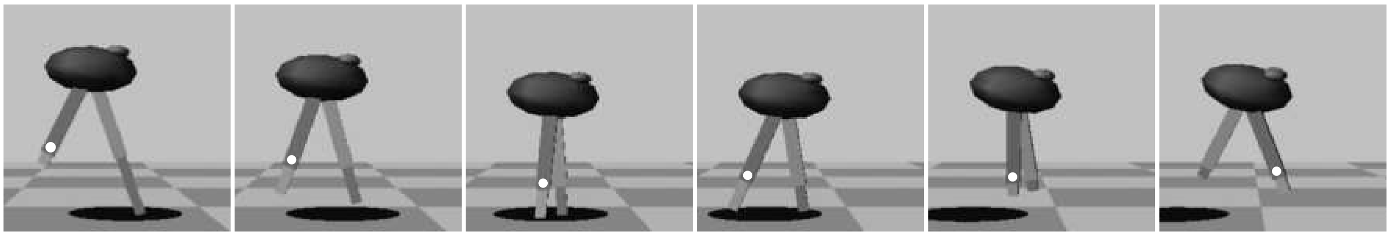

Fig. 14. **Stable Triangle Recovery.** After detecting a slip, the robot forms a stable triangle. Although the legs slip just prior to liftoff, the control system is able to recover because the slip is symmetric and occurs at the end of the step. [Friction coefficient: 0.02. Times (s): 0.0, 0.03, 0.07, 0.10, 0.14, 0.19]

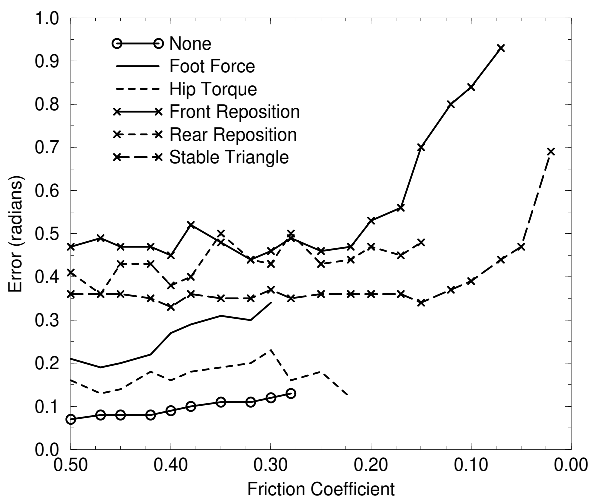

Fig. 15. **Touchdown Errors.** If the robot recovers from a slip, it starts the next step with some error. This graph illustrates the tradeoff between smooth running and slip recovery. Lower curves indicate smaller errors in body and leg angle. Longer curves indicate that a greater range of friction coefficients can be tolerated.

the slips occur at the end of the recovery step. Figure 13 shows a normal ground contact and rebound followed by a slip upon takeoff. Because the hopping height, forward speed, and body attitude control algorithms have already been applied, the slip has little effect on the configuration of the robot. Figure 14 shows slipping upon takeoff for the stable triangle strategy, which applies no attitude correction during the recovery step. However, as Figure 14 shows, both legs slip symmetrically, cancelling the effect of their torque on the body. Thus, the stable triangle reflex is capable of recovering from surfaces with coefficients as low as 0.025.

VI. Tripping

For steady-state running, the control system detects expected events, such as foot contact or initial leg spring compression, and uses these signals to transition between control states. During each state, it applies the appropriate collection of control laws. Tripping occurs when the robot feet or legs encounter unexpected obstacles, causing the controller to execute inappropriate servo commands (Figure 16).

To explore reflexive responses to tripping, we considered the task of returning the robot to steady-state running after

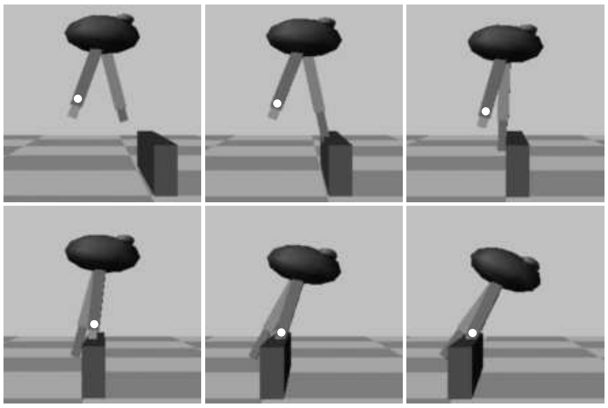

Fig. 16. **Simulated Trip.** The front foot contacts the vertical face of a box and slides down the surface. With no response, the robot is unable to continue running and crashes. [Times (s): 0.0, 0.05, 0.09, 0.13, 0.17, 0.20]

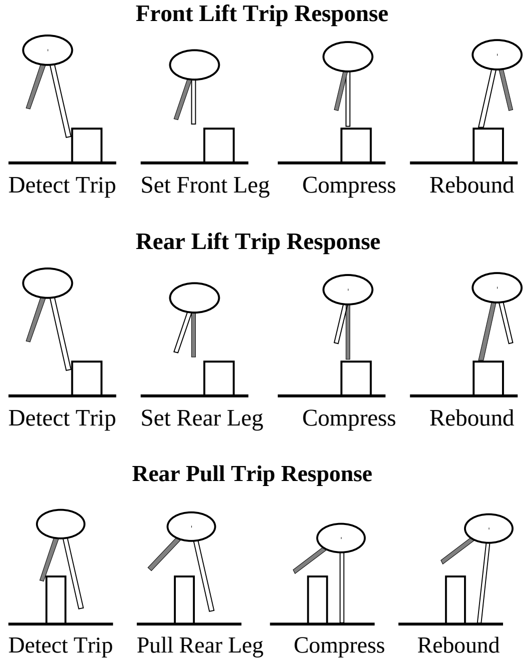

Fig. 17. **Trip Recovery Strategies.** After a trip has been detected, one of the legs is repositioned in an attempt to contact the top surface of the obstacle or avoid it entirely.

a collision with a box. The existing controller allowed the robot to continue running for some unexpected contacts. For example, foot contacts on the top surfaces of boxes, though premature in the flight phase, allowed a normal step to occur. Oblique contacts, such as brushing the side of the box, also did not usually prevent running from continuing. Other contacts, such as a foot or leg contacting the vertical face of a box, resulted in crashes.

A. *Tripping Responses*

As in the case of slipping, the sensing requirements were minimal. The controller detected only that a contact with a foot or leg had occurred. It did not detect where on the leg the contact had occurred. These conditions could be determined on a physical robot with contact sensors on the legs or via the existing joint angle sensors.

When a leg or foot hits the front surface of a box, a foot must be repositioned to find a foothold on or beyond the box. If the forward foot hits the box, either the forward or the rear foot can be retracted and repositioned to contact the top surface of the box, where good footholds are available. We call these strategies the "front lift" and "rear lift" reflexes, depending on which leg is lifted to the top surface of the box. If the rear leg hits a box, the leg can be pulled back, allowing it to pass over the box without contact. We refer to this strategy as "rear pull." These reflexes are diagrammed in Figure 17 and shown in Figures 18, 19 and 20.

B. *Tripping Results*

To test the tripping reactions, boxes of varying heights were placed in the path of a robot running in steady state. For the front lift and rear lift reflexes, the vertical face of each box was divided into 20 impact heights and the robot was released with the front foot 2 cm from the box at each height. For the rear pull reflex, the robot was placed straddling boxes of varying heights with the forward foot making an initial ground contact in a normal running step. As the box height increased, the rear leg eventually contacted the box as it swung forward. In all simulations, the initial forward speed of the robot was varied by a small random factor.

With no reflex responses, the robot was unable to continue running following a trip. The front lift and rear lift response curves show that as the box heights increase, the tripping reflexes are less likely to produce a recovery (Figures 21 and 22). The number of crashes increases as the box height increases. This increase in crashes is due to the increasing distances to the box top as the height increases. If the foot hits the box near the top, there may be sufficient time to lift it to the top of the box. However, as the box height increases, fewer potential contact points are near the top edge of the box.

To measure the disturbance to normal running, we computed the same error measure as was used in the slipping trials. The error measure was the sum of the absolute values of the errors between actual and desired yaw, α, pitch, β, and roll, γ:

$$\text{Error} = |\alpha - \alpha_d| + |\beta - \beta_d| + |\gamma - \gamma_d|\,.$$

The bottom graphs in Figures 21 and 22 show that if the robot is able to recover, it does so with approximately the same error independent of box height.

The front lift reflex causes less touchdown error than does the rear lift reflex. To recover with the front foot, the foot must lift over the box edge, whereas a recovery with the rear foot must move the rear foot from its position behind the robot to the box. The rear lift reflex accumulates more errors during the additional flight time.

With no reflex responses, the robot is unable to recover when the rear leg hits a box of any height. However, Figure 23 shows that pulling the leg back after the initial con-

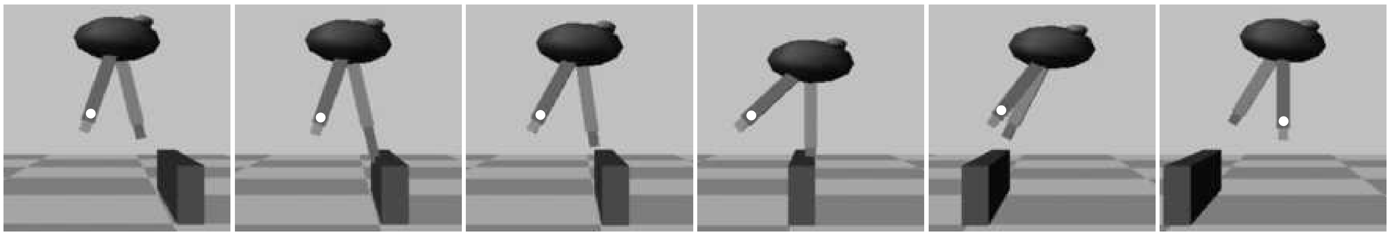

Fig. 18. **Front Lift Trip Response.** The front leg is lifted and repositioned to achieve a better foothold. [Times (s): 0.0, 0.04, 0.06, 0.13, 0.23, 0.27]

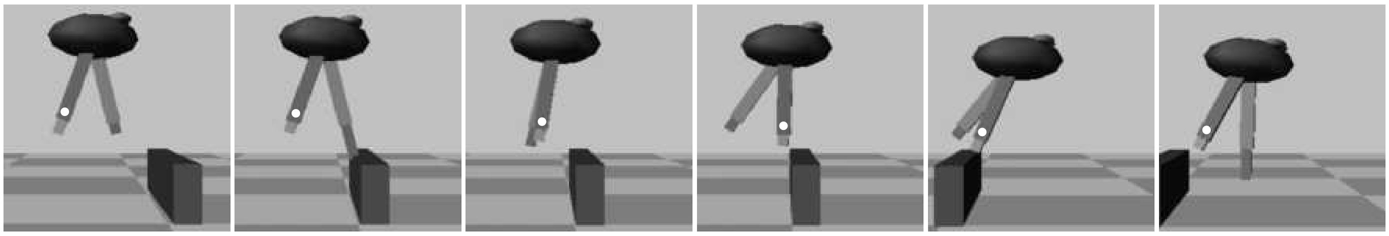

Fig. 19. **Rear Lift Trip Response.** The rear leg is lifted and repositioned to achieve a better foothold. [Time (s): 0.0, 0.07, 0.09, 0.11, 0.23, 0.28]

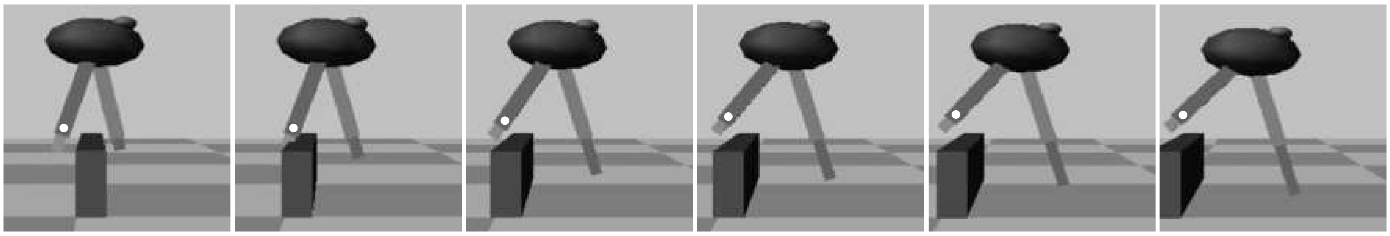

Fig. 20. **Rear Pull Trip Response.** When a leg hits an obstacle while swinging forward, it is pulled back to allow it to clear the obstacle. [Times (s): 0.0, 0.03, 0.06, 0.07, 0.08, 0.10]

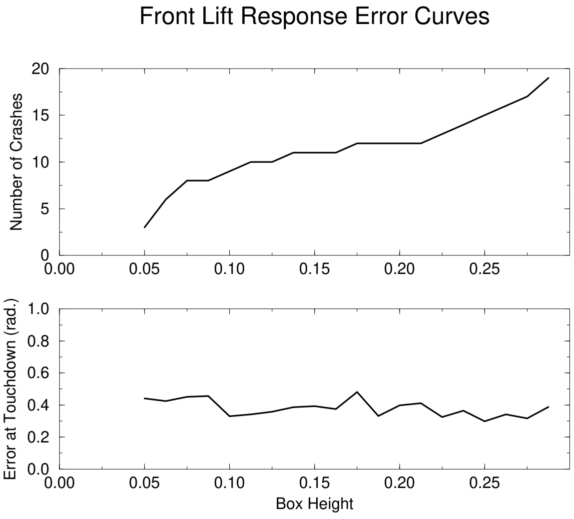

Fig. 21. **Front Lift Results.** The top graph shows the number of crashes as the obstacle height increases. The bottom graph shows the average error in body attitude at the start of the next step after recovering from a trip. As the box height increases, trips more often lead to crashes. Note however, that the errors remain relatively constant for those trials where the robot is able to recover and continue running. There were 20 runs per box height. Box heights below 5 cm did not cause trips; box heights above 28.75 cm did not allow recovery.

tact allows the robot to pass the leg over boxes as high as 23 cm without crashes. For boxes between 23 cm and 25 cm, the leg, though pulled back, hits the box again, but may still be able to recover. Above 25 cm, the boxes are too high for the retracted leg to pass over, increasing the number of crashes.

VII. Discussion and Conclusions

We have considered the problem of creating reflexes for slipping and tripping given only the information that a slip or a trip has occurred. We evaluated two kinds of responses to slipping, one-step strategies and two-step strategies, depending on whether the correction was applied in the slip step or in the following step. Responses that continue the slipping step produce smoother recoveries but only for higher friction coefficients. Responses that abandon the slipping step are capable of negotiating surfaces with a larger range of friction coefficients but accumulate larger errors.

Our slipping simulations focused on traversing a patch in which one footfall slipped; however, some observations can be made regarding running on a slippery surface. For higher coefficients of friction, the strategy with the smallest errors, the hip torque reaction, is most likely to succeed. The repositioning strategies are limited because continual

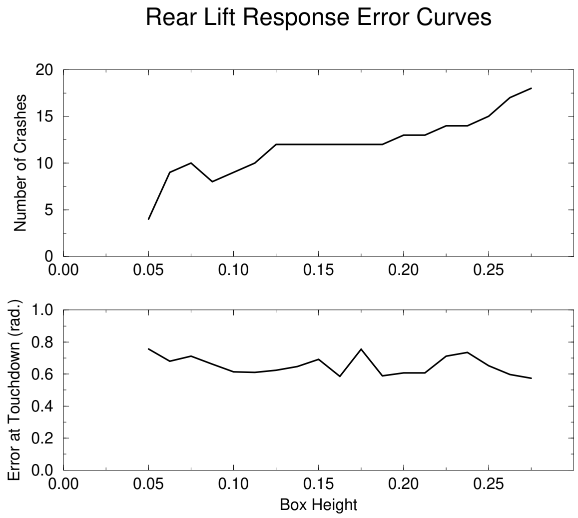

Fig. 22. **Rear Lift Results.** Taller boxes are more likely to cause a crash. However, if the robot does recover, it does so with a relatively constant error. The rear lift reflex recovers about as often as the front lift reflex (Figure 21), but with higher resulting errors. There were 20 runs per box height.

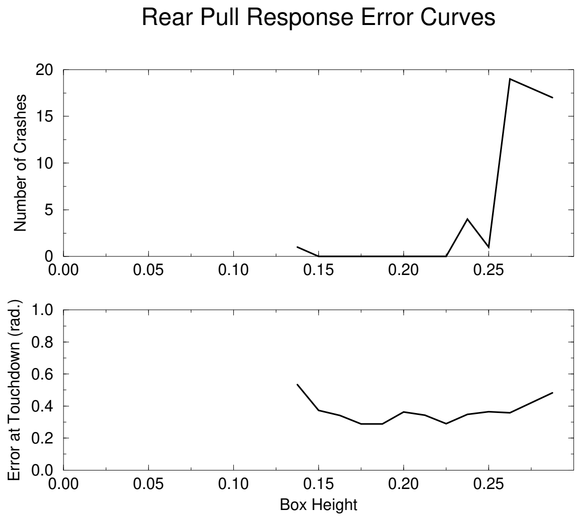

Fig. 23. **Rear Pull Results.** Pulling the tripping foot back so it passes over the box allows the robot to continue running, but with some additional attitude error. For box heights below 13.75 cm, the rear foot passes over the box without tripping due to the retraction of the leg during running. There were 20 runs per box height with variation in the initial velocity of the robot.

slipping would cause them to abandon every other step. However, all of the reflexive strategies except the hip torque strategy reduce the forward velocity during slip recovery, thus making the foot forces more vertical on subsequent steps. Preliminary results indicate that only a few slipping reactions may be required to achieve steady running on a slippery surface without slipping.

If the foot is moving with respect to the ground at touchdown, the horizontal force on the ground is increased in the direction of motion, thereby increasing the danger of slipping. Strategies for running on slippery surfaces should try to reduce the relative motion of the foot between the ground prior to impact. This principle, commonly called *ground-speed matching*, is useful in slip prevention. It also reduces the impact of ground contact and is used by animals and human runners.

We evaluated several reflexes that repositioned the foot after a trip to find a viable foothold or to avoid the box. For trips in which the forward foot struck the vertical face of the box, lifting either the front or rear foot allowed recoveries. However, lifting the front foot produced the smallest errors at the start of the subsequent step. For trips in which the rear leg hit the box, pulling the leg back to let it pass over the box allowed the robot to continue running, but with some additional error in body attitude.

The slipping and tripping reflexes have been validated for single slip or trip tasks. The next task is to integrate the reflexes to enable running through general rough terrain with arbitrary obstacles and slippery areas. Additional controllers may be used to select among the applicable reflexes based on sensing or modeling of the environment. Finally, within the time constraints of the rapidly evolving dynamic system, limited replanning may be used to aid recovery.

These slipping and tripping reflexes are robust despite their minimal sensing requirements. Without determining friction or obstacle properties, without modeling the surface, and without online planning, the reflexes enable the robot to continue running under many circumstances. Even if more sensing and computational resources are available for foot placement, surface modeling, and replanning, reflexes such as these will remain necessary due to sensing and modeling errors.

Slipping and tripping reflexes are fundamental to many rough terrain problems. Slopes, uneven surfaces, and small obstacles create oblique impact angles that can cause slips and trips. Reflexive responses will facilitate the successful traversal of these terrains in combination with other reflexive strategies for foothold errors such as adhesions, bounces, and loss of firm footing.

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