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Biped Gait Transitions

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Abstract

In this paper we describe algorithms for generating biped run-to-walk and walk-to-run transitions. We were able to develop simple algorithms for these gait transitions by designing strategies for transforming the set of oscillations corresponding to one gait into the set corresponding to the other. For example, the gait transition from running to walking removed energy from the vertical oscillation by shortening the leg during the stance phase to initiate walking. We tested this approach by implementing run-to-walk and walk-to-run transitions on a planar biped robot.

1 Introduction

Animals change gaits as they travel at different speeds. Changing gaits allows them to travel faster, more efficiently, and with lower peak loading on their legs. If the legged systems that humans build are to locomote in an elegant and efficient manner, they must also be able to run with a variety of gaits and to switch among them at will.

In this paper we propose algorithms for walk-to-run and run-to-walk transitions for a two-legged robot. We were able to use simple algorithms for these gait transitions. To develop these algorithms we examined the oscillations of each degree of freedom in each gait and designed a strategy for transforming the oscillations occurring in one gait into those occurring in the other. Given control algorithms for two stable gaits and a point in the cycle of each gait where the oscillations are similar, the control system adds or removes energy to transform each oscillation into the corresponding oscillation for the new gait. The control system then switches to the control algorithm for the new gait. For example, to switch from walking to running, the control system could extend the leg during the stance phase to add energy and initiate the flight phase found in running. We explore this approach with a planar two-legged robot. The machine walks, runs, and switches between walking and running. Raibert (1990) used a similar approach when he implemented algorithms for quadruped gait transitions from trotting to bounding, trotting to pacing, and pacing to trotting.

2 Gait Transitions

Gaits can be characterized by the oscillations of the body and legs that occur during each step or stride. For example, bipedal running contains a once-per-step vertical oscillation of the body and legs and a once-per-stride fore-aft oscillation of the legs. Together these two oscillations describe much of the motion that we call bipedal running. Smaller oscillations in forward speed, body attitude, and leg length also occur in bipedal running. Figure 1 shows the vertical bouncing motion and the alternating fore-aft oscillation of the legs in bipedal running.

Bipedal walking can be distinguished from running because the oscillations of some degrees of freedom differ. For similar speeds, the once-per-stride fore-aft swinging of the legs found in walking is larger than that found in running. The vertical oscillation in walking is of smaller amplitude than that found in running. Figure 1 shows the two primary oscillations found in walking.

The highest point of the vertical oscillation occurs at a different time in the locomotion cycle in running and in walking. During running, the body is lowest when the hip passes over the foot and highest in the middle of the flight phase. In walking, the body is highest when the hip passes over the foot and lowest during double support when both feet are on the ground. This phase shift is responsible for the differences between the energy transfer patterns for walking and running. In walking, energy is transferred between kinetic energy and gravitational potential energy. In running, kinetic energy and gravitational potential energy oscillate in phase and energy is stored in elastic elements of the animal or robot (Cavagna and Margaria 1966; Taylor 1978). McMahon (1985) suggests that the characteristic patterns of energy transfer in walking and running provide a better rule for deciding whether a particular pattern of locomotion should be called running or walking than the traditional one of whether the gait includes a flight phase.

Walking and running are both distinguished and characterized by their component oscillations. Gait transitions can be viewed as algorithms that transform one set of oscillations into another. For example, the transition from walking to running could be performed by injecting extra energy into the vertical oscillation to produce the larger oscillation needed for running. More specifically, the control system could

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[†] This work was done when the author was at the MIT Leg Laboratory.

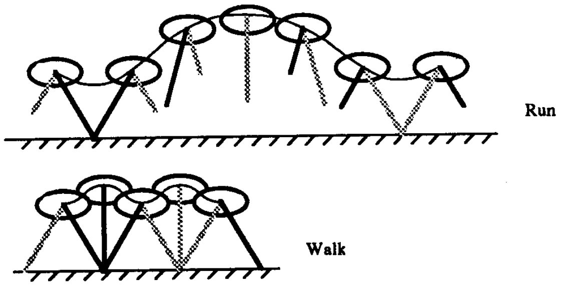

Figure 1: The top drawing shows one step from the motion of a running biped. The body bounces up and down and the legs swing fore and aft in alternation. The bottom drawing shows two steps from the motion of a walking biped. The body moves up and down as it pivots over the leg and the legs swing fore and aft.

lengthen the leg during the second half of stance to add the required energy and initiate the flight phase. The fore-aft oscillation of the legs also differs between the two gaits but because the legs are relatively light compared to the body, the changes in their oscillation can be accomplished without an explicit action during the transition step. The transition from running to walking requires a similar but opposite action to reduce the energy in the vertical oscillation. The control system could shorten the leg during the second part of stance to reduce the energy stored in the spring and cause the system to remain on the ground and allow walking to begin.

3 Experiments

To experiment with algorithms for biped gait transitions, we used a planar, two-legged machine. Figure 2 illustrates the design of the machine. The machine is described in detail in Hodgins, Koechling, and Raibert (1986). In a typical experiment, the planar biped travels around a circle with a running or walking gait. Every 6 ms the control computer collects data from the sensors, executes the control algorithms, sends outputs to the actuators, and records data for later analysis.

In the next three sections stable running and walking gaits for the planar biped are described followed by an account of experiments demonstrating transitions between the two gaits.

3.1 Running

Our algorithm for controlling bipedal running reflects the two primary oscillations found in the gait: one part of the algorithm controls the vertical bouncing motion and a second part determines the amplitude of the leg oscillation. A third controller regulates the attitude of the body.

The vertical oscillation is produced by a passive spring in the leg which compresses and extends during stance. During the stance phase, an actuator in series with the spring is extended or retracted to make up for losses in the system or to produce a higher or lower vertical oscillation. The control system uses a proportional-derivative servo to move the actuator to the desired thrust length.

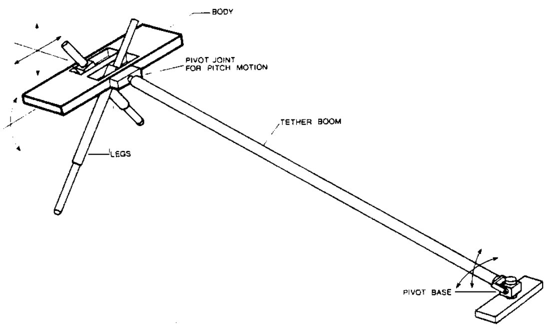

Figure 2: Diagram of the planar, two-legged running machine used for experiments. The body is an aluminum frame on which are mounted hip actuators and computer interface electronics. Each hip has one low friction hydraulic actuator that moves the leg fore and aft. An actuator within each leg changes its length, and an air spring makes the leg springy in the axial direction. Sensors measure the lengths of the legs, the positions and velocities of the hip actuators, pressures in the air springs, contact between the feet and the floor, and the pitch angle of the body. An umbilical cable connects the machine to hydraulic, pneumatic, and electrical power supplies and to the control computer, all of which are located nearby in the laboratory. A tether boom constrains the machine to move fore and aft, up and down, and to rotate about the pitch axis.

The fore-aft oscillation of the legs is formed by the backward motion of the leg while the foot is on the ground and the forward swing of the leg as it is positioned for the next touchdown. The control system swings the leg forward to the position that will produce steady-state running at the desired forward speed. The placement of the foot at touchdown is

$$x_{fh} = \frac{T_s \dot{x}}{2} + k_{\dot{x}}(\dot{x} - \dot{x}_d),$$

where T_s is the expected duration of the next stance phase, $\dot{x}$ is the forward speed, $\dot{x}_d$ is the desired forward speed for the next flight phase, and $k_{\dot{x}}$ is an empirically determined gain. The first term in the equation provides feedforward control of forward speed for steady-state running and the second term provides stabilization for disturbances or changes in desired forward speed. A proportional-derivative servo is used to move the leg to the correct angle before touchdown.

The third controller corrects for disturbances to the body attitude caused by the swinging motion of the legs and by the interaction of the leg with the ground at touchdown. The control system uses the actuator between the body and the leg to bring the body back to level during each stance phase:

$$\tau = k_p \phi + k_v \dot{\phi}$$

State and Trigger Event	Actions
FLIGHT Active leg leaves ground (liftoff)	Interchange active and idle legs Lengthen active leg for landing Position active leg for landing Shorten idle leg Mirror angle of active hip with idle hip
LOADING Active leg touches ground (touchdown)	Keep active leg at touchdown length Zero active hip torque Keep idle leg short Mirror angle of active hip with idle hip
COMPRESSION Active leg air spring shortens (support)	Keep active leg at touchdown length Servo pitch with active hip Keep idle leg short Mirror angle of active hip with idle hip
THRUST Active leg air spring lengthens (bottom)	Extend active leg Servo pitch with active hip Keep idle leg short Mirror angle of active hip with idle hip
UNLOADING Active leg air spring approaches full length (no support)	Shorten active leg Zero hip torques active leg Keep idle leg short Mirror angle of active hip with idle hip

Table 1: Finite state machine that coordinates two-legged running. The state shown in the left column is entered when the trigger event occurs. During that state the control system performs the actions listed in the right column. Each state listed in the table occurs twice in each stride, once when leg 1 is active and once when leg 2 is active.

State and Trigger Event	Actions
SUPPORT RISING Rear leg leaves ground	Correct body attitude with stance leg Keep stance leg at touchdown length Shorten swing leg to clear ground Position swing leg for landing
SUPPORT FALLING Hip in front of stance foot and behind swing foot	Correct body attitude with stance leg Keep stance leg at touchdown length Lengthen swing leg for touchdown Position swing leg for landing
DOUBLE SUPPORT Touchdown of swing leg	Correct body attitude with both legs Keep front leg at touchdown length Thrust with rear leg

Table 2: Finite state machine that coordinates two-legged walking. Each state listed in the table occurs twice in each stride, once when leg 1 is in front and once when leg 2 is in front.

where τ corresponds to the torque applied between the leg and the body, ϕ is the angle of the body with respect to horizontal, $\dot{\phi}$ is the velocity of the body angle, and k_p and k_v are empirically determined gains.

The actuators in the legs and between the body and the legs are used for different tasks during different phases of the running cycle. Table 1 describes how the control actions are coordinated with the motion of the legged system. The algorithm for bipedal running is described in greater detail in Hodgins, Koechling, and Raibert (1986).

3.2 Walking

Like running, walking consists of a vertical oscillation and a fore-aft swinging of the legs; therefore, the same three-part division of the control algorithm can be used for both gaits: one part controls the vertical oscillation through leg extension during stance, a second part controls the fore-aft oscillation of the legs through the selection of a forward foot position, and a third part controls the attitude of the body. A state machine is used to coordinate the controller actions with the physical motion of the legged system (table 2).

The vertical oscillation in walking differs from the vertical oscillation in running because the leg spring does not compress significantly. Instead, the vertical oscillation is caused by the rise and fall of the body as it pivots over the stance leg. Despite these differences, the same control strategy can be used to control the vertical oscillation in both walking and running: a fixed extension of the leg actuator during stance. The gains for the servo are lower and the leg actuator is extended more slowly in walking.

The fore-aft oscillation of the legs is controlled through the selection of a forward foot position for the next touchdown. The forward foot position in our implementation of walking is a fixed distance in front of the hip ($x_{fh} = k$ where k is a constant) and does not include feedback for the control of forward speed.

The third part of the walking controller regulates the attitude of the body. This controller is identical to that used in the control of running—a proportional-derivative controller brings the body back to level by generating a torque between the stance leg or legs and the body.

Walking can be passively controlled. McGeer (1990) has elegantly demonstrated this by building a walking machine with no explicit control system. His machine walks stably down an inclined surface with only the mechanical control built into the system through the choice of masses, link lengths, and appropriate initial conditions. The legged system described here is powered and uses computer control, but the design of the walking controller was inspired by the ideas on passive walking put forward by (Margaria (1976), Mochon and McMahon (1980), and McGeer (1990)).

Although this simple algorithm for walking was sufficient for the results reported here, it was not as robust as the algorithm for running. The machine sometimes walked with a limping gait: a fast step on one leg and a slow step on the other. Walking failed when the external disturbances were too large. The cables connecting the machine to the hydraulic power supply sometimes provided enough drag that the machine slowed down and fell backwards. We plan to implement more robust walking by using feedback to respond to external disturbances.

3.3 Gait Transitions

Our approach to gait transitions involves examining the component oscillations of each gait. The left graph of figure 3 illustrates the vertical bouncing motion of the body; the right graph shows the fore-aft swinging motion of the legs as the machine ran forward at 0.75 m/s. Figure 4 shows the behavior of the machine as it walked at approximately the same speed (0.85 m/s). The vertical oscillations are similar in shape for the two gaits although the oscillation in run-

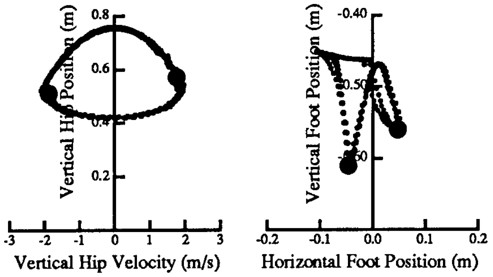

Figure 3: The left graph shows the vertical bouncing motion of the body during running. The top half of the graph reflects the motion of the system as it falls under gravity; the bottom half of the graph shows the stance phase when the system behaves like a mass-spring oscillator. Time increases around the graph in a counter-clockwise fashion. The large circle on the left side of the graph shows the body's position when the foot touches the ground; the circle on the right side shows its position at liftoff. The right graph shows the fore-aft and up-down oscillation of one foot with respect to the hip during running. The circle on the right side indicates touchdown and the one on the left indicates liftoff. During stance the leg spring first compresses and then extends. At liftoff the leg is first shortened and then swung forward in preparation for the next stance phase. During the next flight phase, the leg is extended for touchdown.

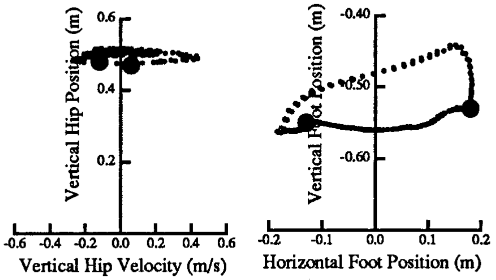

Figure 4: The left graph shows the vertical oscillation that occurs during walking. The top of the graph reflects the portion of the cycle when only one leg is on the ground. The body reaches its highest point when the hip passes over the foot. The bottom portion of the graph (between the two circles) represents the period of double support when both feet are on the ground and the body is at its lowest point. The circle on the left indicates touchdown of one leg and the one on the right indicates liftoff of the other. The right graph shows the fore-aft and up-down motion of one foot with respect to the hip. The bottom portion of the graph illustrates the period when the foot is on the ground, the top portion illustrates the motion when the foot is swung forward in preparation for the next touchdown.

ning is much larger in magnitude. The fore-aft swinging motion is similar for the two gaits but the pattern of lengthening and shortening of the leg is different because the leg spring does not compress during walking. The fore-aft oscillation of the legs has a larger magnitude in walking than in running because there is no flight phase and the legs are on the ground for a larger fraction of the step.

Figures 5 and 6 show data for gait transitions from walking to running and running to walking. In figure 5 the vertical dotted lines indicate where the control system began lengthening the leg to add energy to the vertical oscillation and initiate running. The gait transition occurred when only one leg was on the ground. To add energy to the vertical oscillation, the stance leg was extended by a fixed amount using the leg extension servo for running. When the force on the foot was small and the leg was nearly at full extension, the control laws were switched to those for the flight phase of the running gait.

In figure 6 the vertical dotted lines indicate where the control system began shortening the leg to reduce the vertical oscillation and perform the gait transition from running to walking. The gait change occurs in the middle of stance when the spring was at maximum compression. To remove energy from the vertical oscillation, the leg actuator is retracted by a fixed amount using the same gains as the servo used in running. The control laws are switched to those used in the first half of the stance phase in walking. The leg extension that normally occurs during the second part of stance in walking is eliminated for the transition step.

Both gait transition algorithms performed reliably. Gait transitions from walking to running were very reliable (60 successful transitions of 60 trials). Gait transitions from running to walking were slightly less reliable (57 successful transitions of 60 trials). Failures in the running to walking transitions occurred when too much energy remained in the leg spring after the retraction of the leg actuator and the machine bounced off the ground before the second leg touched down. The algorithms did not include any explicit error recovery and the control system failed to recognize that no feet were on the ground.

The left graph in figure 7 shows the vertical motion of the body during a gait change from walking to running. The inner cloud of dots shows the vertical oscillation during walking and the outer circle shows the motion during running. The path between the two circles shows the motion of the body during the gait transition from walking to running. The right graph of figure 7 shows the vertical motion of the body during a gait change from running to walking.

The actions taken for the two gait transitions are nearly equal and opposite: for the walk-to-run gait transition the leg is extended a fixed amount and for the run-to-walk gait transition the leg is retracted a fixed amount. After the extension or retraction of the leg, the control laws are switched to those for the corresponding state in the other gait. These nearly symmetric actions produce nearly symmetric patterns of motion. The walk-to-run transition is very similar to the run-to-walk transition played backward in time.

4 Discussion

We have implemented two other biped gait transitions: transitions from running to one-legged hopping and from running to flipping. In Hodgins, Koechling, and Raibert (1986) we describe a gait transition from running to hopping on one leg. The oscillations for the body and the active leg are the same for these two gaits and the control system does not take explicit ac-

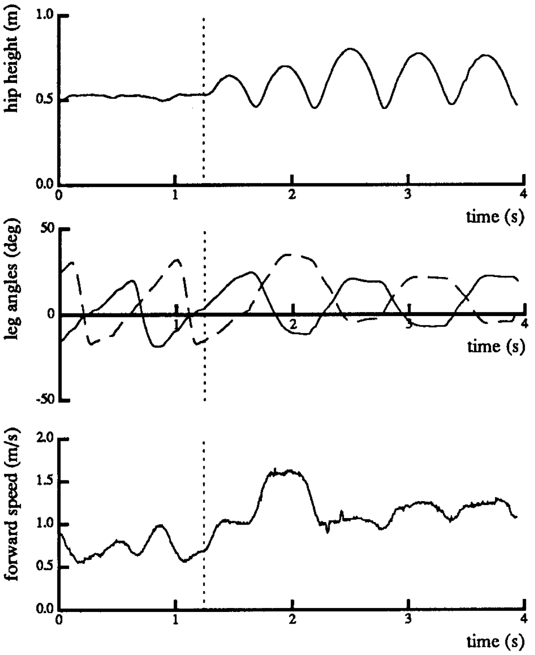

Figure 5: Graphs showing the motion of the body and legs during a gait transition from walking to running. In the graph of hip angles, one leg is shown as a solid line and the other as a dashed line. The control system increased the desired thrust to begin the gait transition at the point indicated by the vertical dotted lines. The gait transition causes an initial increase in forward speed before the machine returns to approximately the same speed as before the gait transition. The hopping height increases for several steps after the gait transition before reaching a steady-state value.

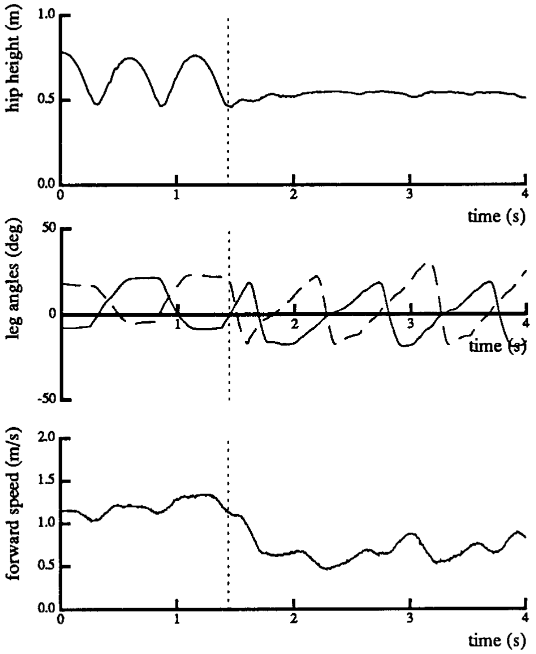

Figure 6: Graphs showing the motion of the body and legs during a gait transition from running to walking. In the graph hip angles one leg is shown as a solid line and the other as a dashed line. The control system shortened the leg to begin the gait transition at the point indicated by the vertical dotted lines.

tion to modify the oscillations but only switches the control law from one gait to the other during flight.

In Hodgins and Raibert (1990) we describe an algorithm that allows the planar biped to perform a forward flip. In our implementation the flip is not a true gait because the cycle does not repeat—the biped does not perform several flips in a row. Nevertheless, the steps preceding and following the flip can be considered gait transitions because the control system alters the oscillations of the body and legs and switches to new control laws for the flip step. The oscillations in the flip step are similar to those found in two-legged running except that the body and legs rotate 360° during the step (figure 8). To produce the pitch rotation for the flip, the control system uses the hip actuator to generate angular momentum during the stance phase preceding the flip. During the flip step, the vertical oscillation is also increased to allow extra time for the rotation. To produce the higher vertical oscillation, the control system uses maximum thrust on the two steps preceding the flip step. The recovery step following the flip is a gait transition back to running. The actions in the recovery step are approximately equal and opposite to the actions taken to the produce the flip: the thrust is reduced and the body attitude controller is used to remove the pitch rotation.

The approach taken in this paper is similar to the one used by Hollerbach (1981) for handwriting. He produced handwriting patterns by combining horizontal and vertical oscillations in the plane of the paper. The transitions between letters were achieved by transforming one oscillatory pattern into another. Each simple letter (a cursive *e* and *l*, for example) could be thought of as a gait and the action of transforming one oscillation into the other is analogous to the gait transitions described here. In the case of handwriting, the same controller is used for all letters but in our implementation each gait has a different controller and the control system not only takes action to modulate the oscillations but also switches to the control laws for the new gait.

Bipeds normally run with only two or three gaits but quadrupeds have more legs, more gaits, and more complex gait transitions. One measure of the complexity of a gait transition is the number of oscillations that differ between the two gaits. Planar biped walking and running have significant differences only in the vertical oscillation; therefore, the gait transitions demonstrated here are not complex. Some three-dimensional biped and quadruped gait transitions will be more complex and will involve the modification of two or three oscillations. It is not clear whether this simple approach of modulating the component oscillations of the gaits will be sufficient for more complex gait transitions. Cou-

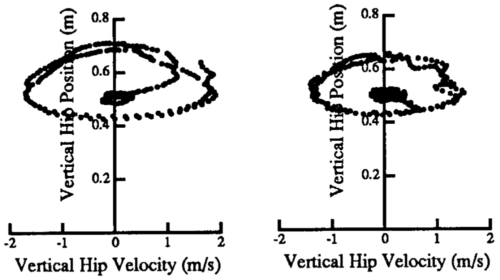

Figure 7: The left graph shows the vertical motion of the body during a gait change from walking to running. The inner circle of dots shows the vertical oscillation during walking (the two steps before the gait change) and the outer circle shows the vertical oscillation during running (the two steps after the gait change). The line connecting the two circles shows the motion of the body during the gait change. The right graph shows similar data for a gait change from running to walking. The leg extension used in running is 0.03 m and that used in walking is 0.04 m; on the walk-to-run transition step the leg extensions is 0.09 m; on the run-to-walk transition step it is -0.07 m.

pling between the various oscillations may become an important consideration.

In the experiments described in this paper we selected a simple scenario for walk-to-run and run-to-walk gait transitions: we chose a speed at which the robot could either walk or run and instructed the control system to change gait every twenty steps. In the intervening nineteen steps the robot used one of the two gaits at a nearly constant forward speed. Animals running freely generally perform gait transitions as part of an acceleration or deceleration phase that lasts for more than one step. Animals probably use this pattern because each gait is most efficient at a particular speed (Hoyt and Taylor 1981). The intervening speeds are less efficient and are used for only brief periods of acceleration or deceleration. Each robot gait will also most likely be most efficient at a particular speed. The control algorithms for gait transitions will need to be incorporated into longer acceleration or deceleration phases.

The ability to change gait naturally leads to the question of when to change gait. Animals appear to switch gait at approximately the speed where the oxygen consumption curves of the two gaits cross. The selection of gait has some hysteresis, however, because walk-to-run gait transitions for humans occur at slightly higher speeds than run-to-walk gait transitions (Alexander 1989; Thorstensson and Roberthson 1987). We do not have experimental measurements for robots that indicate which gaits are efficient and in what speed ranges. It will be interesting to learn how the efficiency issues differ between biological legged systems and the robots we build.

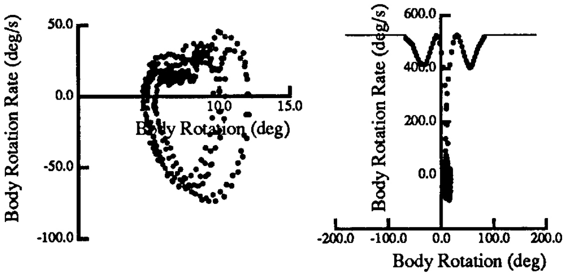

Figure 8: The left graph shows the pitching oscillation during the six steps that preceded a flip. The right graph shows the pitching oscillation that occurred during a gait change from running to flipping and back to running. The cluster of points near zero are the running steps before and after the flip. In the flip step the pitch angle begins at zero and increases through 180° to -180° and back to zero. The body rotation rate during the flip reflects the acceleration of the legs up to the rotation rate of the body and the shortening of the legs to decrease the moment of inertia of the system. The sensor which measures the body attitude did not operate over the full 360°, the data when the machine is upside down are interpolated and are shown as a solid line. (Data from Hodgins and Raibert 1990)

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