5. WALKING VARIATIONS

The ability to control walking characteristics such as speed, direction, stride rate and posture is important if a system is to be seriously considered as an animation tool. This chapter first introduces an approach to controlling the speed of a walk without requiring changes to the underlying base PCG. Next, the idea of using parameterized base PCGs is introduced and a number of interesting variations on the basic walk are described.

The idea of parameterizing an open-loop control structure such as PCGs is not entirely new [vKF94b]. However, the successful parameterization of dynamically unstable motions such as walking does represent an important advance.

5.1 Speed Control

The basic balance control discussed in Chapter 3 uses fixed values of Q^d for all steps of a walk and achieves constant walking speeds. One possible way to vary the speed of a walk is to provide a number of base PCGs which yield various speeds and interpolate between these. This approach might be somewhat cumbersome, however, since it requires the animator to provide suitable base PCGs. An alternative is to allow Q^d to vary from one step to the next instead of remaining fixed. By varying Q^d to cause the biped to speed up or slow down each step, a wide range of walking speeds is possible without requiring modifications to the base PCG. This approach requires that we be able to affect the speed of the walk in a consistent manner by varying Q^d. Whether or not this is possible depends on the choice of control system parameters (RVs, LPPs, etc.). With the choices described in Chapter 3, an intuitive form of control is available. In qualitative terms, an increase in speed can be achieved by using a more forward-leaning value for Q^d and a decrease in speed can be achieved using a more upright value for Q^d.

More formally, to control walking speed, $\tilde{Q}^d$, a new value for Q^d is computed each step by adding a velocity feedback term to a nominal value of Q^d as follows:

$$\tilde{Q}^d = Q^d_{bias} + k_p \cdot (v_d - v) \qquad (5.1)$$

where

Q^d_{bias}	is a nominal bias value
v_d	is a desired speed
v	is a measure of the speed of the current step
k_p	is a proportional feedback gain

The bias value is required because the required Q^d for a stationary walk (i.e. in-place) is not necessarily 0. The feedback term adjusts $\tilde{Q}^d$ in the appropriate direction (more forward or more upright) by an amount proportional to the error in speed. We choose to use the distance travelled by the pelvis over the current step as a velocity measure for v and v_d.

The speed of the walk can be varied using either v_d or Q^d_{bias}, since both contribute a constant term to the overall equation. Fixing v_d and varying Q^d_{bias} is akin to choosing a nominal speed and varying the actual speed about that point by leaning more forward or more upright.

To prevent excessively large accelerations that could cause a fall, the feedback term is limited in magnitude:

$$\left| k_p \, \Delta v_d \right| \;\leq\; \Delta Q_{max},$$

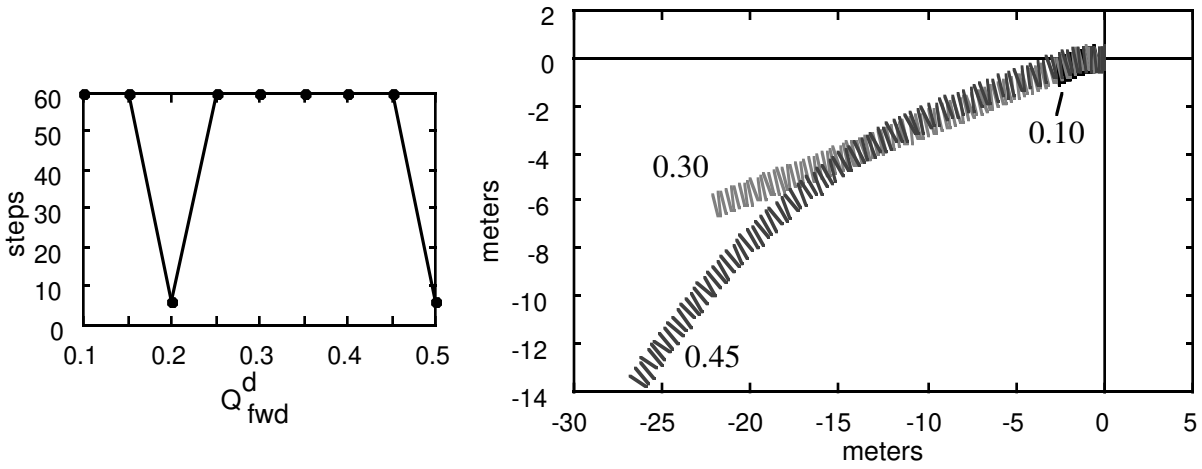
where ΔQ_{max} is the maximum allowable change in $\tilde{Q}^d$ from Q^d_{bias}

Q^d_{bias} can be taken from any successful walk. In theory, we could use the Q^d value which gives a stationary walk to reach any desired speed. In practice, it may be necessary to choose a few nominal bias values near the various desired speeds to achieve the broadest possible range of control. Other parameters require some trial-and-error. k_p must be chosen to relate a required change in speed to a suitable change in Q^d. If k_p is too large, the system will be too sensitive to small errors in speed and fall easily. If k_p is too small, the system may not respond quickly enough to prevent a fall. The size of the range of constant Q^d values which produce successful (constant speed) walks for the given base PCG is typically a reasonable value for ΔQ_{max}.

Figure 5.1 shows the nominal RV range and hip plots of a series of trials using speed control with balance parameters based on Figure 4.1. The trials of Figure 5.1 use a composite choice of RVs, consisting of a forward up vector RV component and a lateral swing-COM RV component. This is done to avoid the tightrope walking and uneven step length associated with each, respectively. The hold times for each time-based transition of the base PCG have been increased from 0.2 to 0.25 to yield a natural stride rate of 1.0 steps/second. Speed control parameters for each control dimension are shown in Table 5.1. A nominal desired speed of 0.4 meters per step or 0.8 m/s is chosen. Q^d_{bias} is varied to generate various speeds around this operating point.

Table 5.1 - Speed control parameters

	K_p	$\Delta Q_{\max}$	Q^d_{bias}	v_d
fwd	1.5	0.15	0.1 - 0.5	0.4
lat	0.5	0.05	±0.03	0.0



(a) (b)

Figure 5.1 - Speed control using composite RV and stride time of 1.0 seconds. Only select Q^d values are shown on hip plot. Other paths are similar in direction with varying lengths. The biped initially faces left (i.e. in the -x direction).

The resulting walks exhibit a number of desirable characteristics:

1. Applying speed control results in a wider nominal range for Q^d.
2. The use of a composite RV and the desired lateral speed of 0 are both effective in eliminating a number of the artifacts in earlier walks. The walks generally follow a straight line for a large range of Q^d, with consistent step length from one step to another and no tightrope walking or leg crossing.
3. A wide range of speeds is possible, with linear control of the steady-state speed about the chosen nominal speed. All walks begin from a stop and reach steady-state speed within around 8 steps.
4. A very slow walk, almost in place, is possible (Q^d_{bias} = 0.1). Note that this walk is outside the linear range of control.
5. Acceleration and deceleration is possible as shown in Figure 5.4.

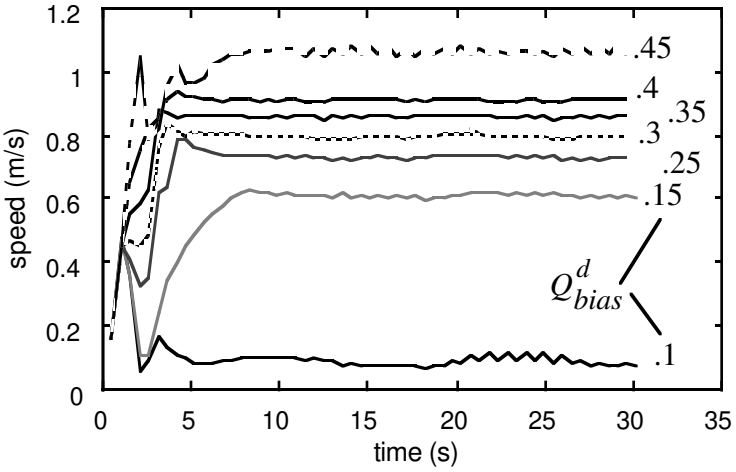


Figure 5.2 - Forward velocity (m/s) versus time for velocity feedback using various base RV target values.

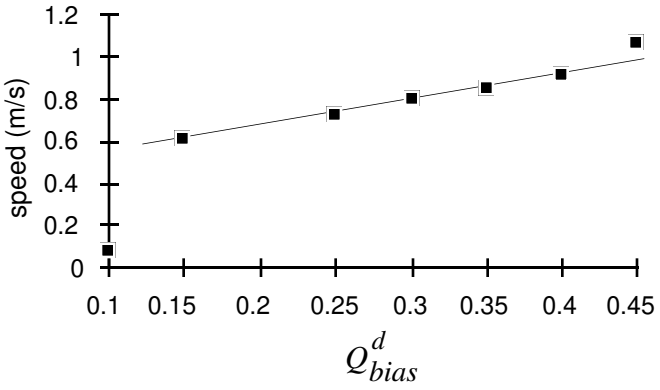


Figure 5.3 - Steady-state velocity vs Q^d_{bias}

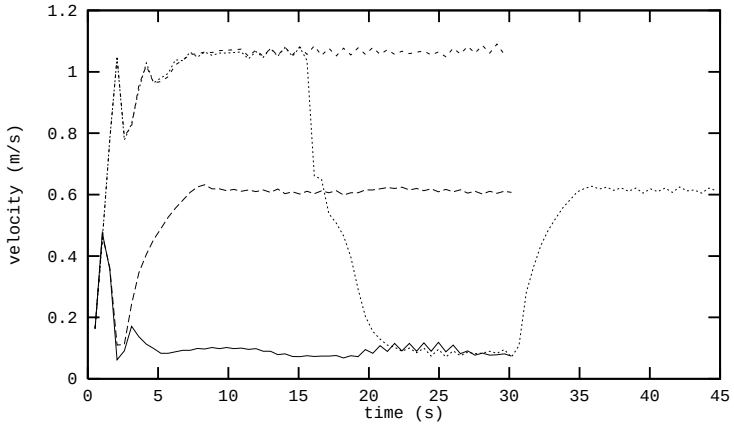


Figure 5.4 - Acceleration and deceleration

5.2 Base PCG Parameterization

By applying the balance control of Chapter 4 to various base PCGs, it is possible to achieve controlled variations on basic walking motions such as balanced turns, bent over walks, and different stride rates. A more powerful feature of these gait variations is that they can sometimes be predictably interpolated. That is, given two different styles of walking, based on PCGs B1 and B2, it is possible to interpolate the control in order to obtain a motion that qualitatively interpolates the respective motions.

More precisely, the interpolation procedure can be described as follows:

> Define β as the balance control process which operates on a base PCG to balance it as described in Chapter 3.
>
> Given *B1* and *B2*, the parameter sets defining two base PCGs, and given that $\beta(B1)$ and $\beta(B2)$ are both successful (i.e. that they don't fall), we often find that the control interpolation
>
> $$\beta(\alpha B1 + (1 - \alpha)B2)$$
>
> varies smoothly with α and is qualitatively similar to what we might imagine a physically correct motion interpolation to be, namely
>
> $$\alpha\beta(B1) + (1 - \alpha)\beta(B2).$$

There is no guarantee that any such successful interpolation exists. In practice, however, smoothly interpolating parameterizations can be found often enough to make them useful.

Such parameterizations can equivalently be thought of as a *linear parametric perturbation* which modifies the open-loop behaviour of a base PCG. The perturbations are identical in form to the balance control LPPs of Chapter 3, but differ in function. Instead of providing step-to-step variations for balance, the perturbations presented in this chapter are applied over a number of steps and are used to vary the overall behaviour of a balanced base PCG in order to achieve a different motion from the original. By recasting the interpolation described above as an LPP, it can then be applied directly to other base PCGs to hopefully effect a similar qualitative change in the motion. For example, if $\beta(B1)$ walks straight forward and $\beta(B2)$ turns to the right, then

$$\Delta P = B2 - B1$$

might be called a turning LPP and could be applied to various other basic gaits to allow them to turn.

This is the interpretation we shall build on in the rest of this chapter.

5.3 Turning Perturbations

One important parameterized perturbation can be used to achieve turning motions. When applied to the base PCG of Section 3.4 and subsequently controlled for balance, this perturbation provides a means to smoothly vary the curvature of the biped's path. Furthermore, by applying a simple proportional control law to determine a suitable turning rate, the biped can be made to follow an arbitrary direction and thus the path of the biped can be controlled.

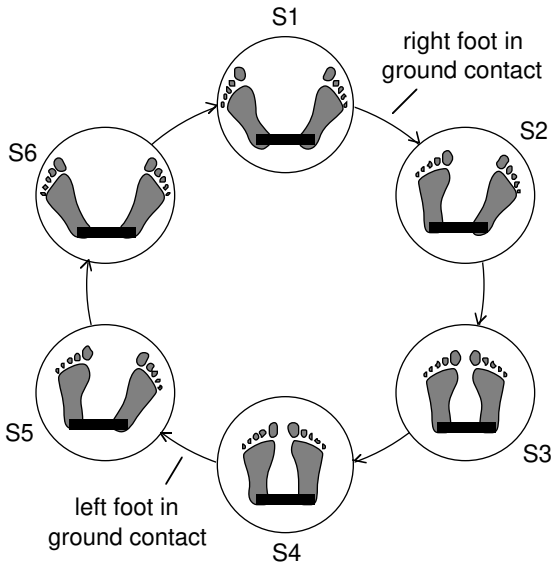
Figure 5.5 (a) and (c) show the PCG perturbation for a right turn for the human model. The perturbation affects only the left and right hip yaw DOFs (3:2 and 6:2). The conceptual operation of the perturbation is straightforward. In order to cause the biped to turn, the foot is placed on the ground at an angle which points toward the new direction of travel. During the stance phase, the hip realigns the body with the foot, which remains fixed relative to the ground.

DOF:		1	2	3:0	3:1	3:2	4	5:0	5:1	6:0	6:1	6:2	7	8:0	8:1	transition info
	S1	0	0	0	0	1	0	0	0	0	0	-1	0	0	0	0
	S2	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0
state	S3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	S4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	S5	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0
	S6	0	0	0	0	1	0	0	0	0	0	-1	0	0	0	0

(a)

DOF:		1	2	3:0	3:1	3:2	4	5:0	5:1	6:0	6:1	6:2	7	8:0	8:1	transition info
	S1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	S2	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
state	S3	0	0	0	0	1	0	0	0	0	0	-1	0	0	0	0
	S4	0	0	0	0	1	0	0	0	0	0	-1	0	0	0	0
	S5	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
	S6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

(b)



(c)

Figure 5.5- Turning perturbations for human model with ball-and-socket hips (DOF 3:2 and DOF 6:3).
(a) Unit-scaled right turning perturbation
(b) Unit-scaled left turning perturbation
(c) State diagram of relevant DOFs for right turning perturbation. Feet indicate hip twist with respect to pelvis.

For the right leg of the right turning perturbation, the initial foot rotation is performed during the swing phase of the right leg, as shown in state 5 of Figure 5.5 (c). During the right leg stance phase, this rotation is eliminated. The return rotation is done in the second stance state (S3), thereby ensuring that the foot is planted firmly on the ground (in S2) before attempting to turn the body. Ground friction keeps the foot position and orientation fixed, while the torso rotates about the leg. The left foot performs a similar motion in its stance phase to distribute the complete rotation evenly over both feet. A similar and symmetric set of perturbations is used for turning to the left. Figure 5.6 shows the typical action of the turning perturbation. For the sake of clarity, the motion is illustrated for the case of a stationary stepping motion.

Figure 5.7 shows the hip plots from a set of turning trials performed using a base PCG similar to that of Figure 3.7. The trials use up vector RVs with Q^d = [.25,0]. As can be seen, the turning control works well for each of the three sampling strategies. Each trial uses a different scaling of the turning perturbation in Figure 5.5. The largest scaling factor used which still yields forward motion corresponds to a hip yaw of 8 degrees for each leg, giving a turning radius of approximately 2.5 meters. All of the walks face slightly into the centre of the circle, an effect which is more pronounced for tighter curves.

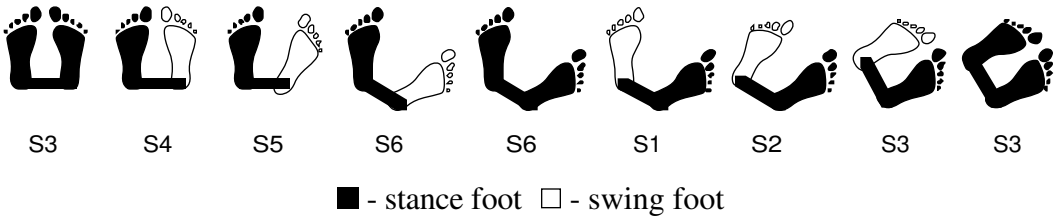
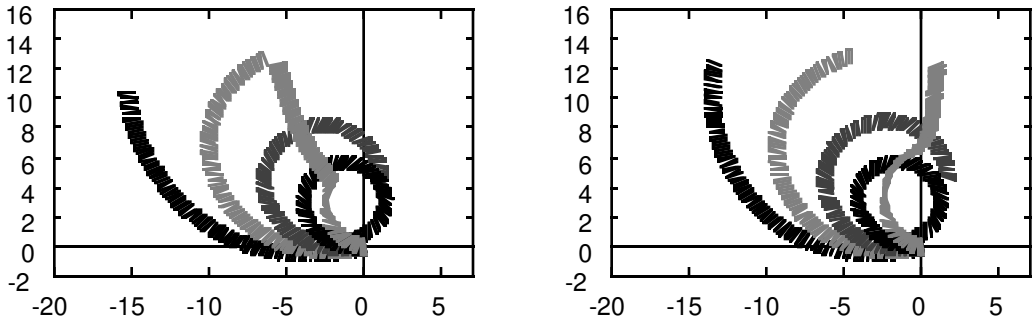


Figure 5.6 - Typical operation of a right turn perturbation for an in-place stepping motion. A top view of the feet and pelvis is shown, with the associated PCG state indicated below.

The largest scaling-factor trials attempted, corresponding to 16 degrees of right and left hip yaw, demonstrates an interesting behaviour. In such trials, the tendency to "lead" the turn with the

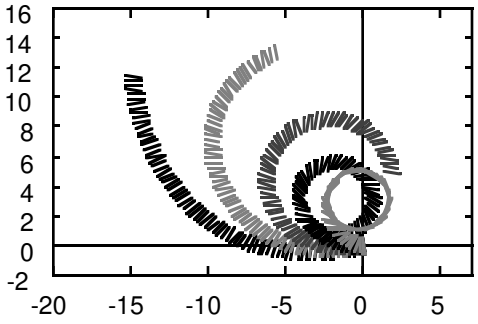
torso rotation causes the biped to rotate about its own vertical axis more quickly than it can move along a circular path. As a result, it turns to face the centre of the circle.

In the F-L and L-F sampling trials, the highest turning rates eventually cause the biped to turn around completely and walk almost straight backwards. The turning perturbation is ineffective in the backward walking cases because the model walks primarily on its heels. As a result, the foot never obtains sufficient ground reaction forces to fix the foot's orientation.



(a) - F-L sampling

(b) - L-F sampling



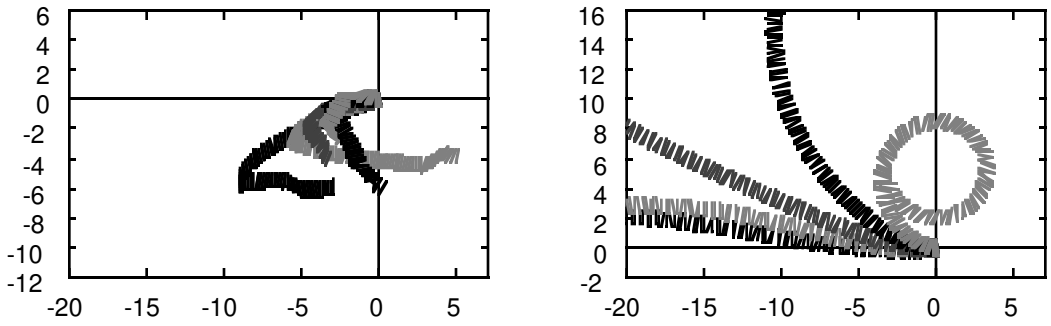
(c) - SP sampling

Figure 5.7 - Hip plots for the most successful turning perturbation trials over a range of scaling factors. Q^d = [.25,0] for all trials.

Not all values of Q^d work equally well as Figure 5.8 demonstrates. Linearly varying the perturbation scaling factor still yields smooth behaviour, but not the desired results of Figure 5.7. While this result makes it clear that some care must be taken in choosing parameters, it also serves to illustrate the fact that reasonable choices can often be made without exploring a large parameter

space through brute force experimentation. Here, the clue lies in the fact that the value of Q^d=[.25,0] is around the centre of the range of nominal Q^d values for the straight forward walks of Figure 4.3. This suggests that this value of Q^d might be best for other similar PCGs.

One deficiency of the walks of Figure 5.7 is that the smallest successful turning radius is approximately 2.5 meters. While this is adequate for navigating the biped in a relatively open environment, it is too large for motion in a constrained environment such as turning a corner in a narrow corridor.



(a) Q^d = [.2,0] (b) Q^d = [.3,0]

Figure 5.8 - Hip plots for less successful turning perturbation trials over a range of scaling factors.

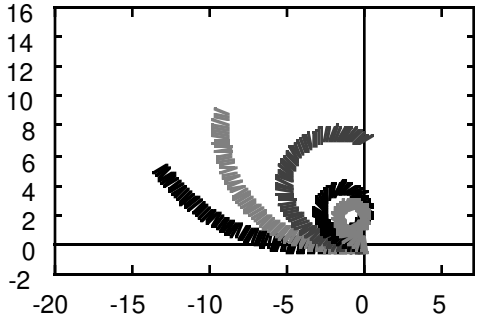


Figure 5.9 - Turning perturbation with torso servoing applied.

Applying torso servoing during turning helps significantly, as indicated by Figure 5.9. With torso servoing to an angle of 5 degrees from vertical, the walk is slower and the circles can be

tighter. The 16 degree turning perturbations fail, resulting in a turning limit cycle of approximately 0.75 meters in radius, a more useful lower limit in terms of the motion that can be animated. The walks still suffer from the biped facing too much toward the centre of the turn. For tight turns, the biped's outside swing leg interpenetrates the stance leg in a noticeable fashion. Nonetheless, the perturbations provide a good basis for higher level control of the biped's path.

5.3.1 Point and Path Following

By applying simple feedback control, the biped can be made to walk in a desired direction. Proportional control of the angle of the current facing direction and the desired direction as given by a target point is used to generate an appropriate turning rate.

The pose control applied each step including balance control is the same form as Equation 5.1.a:

$$(B + k_{turn}\Delta P_{turn}) + k_1\Delta P_1 + k_2\Delta P_2$$

In the case of separate left and right turning control perturbations,

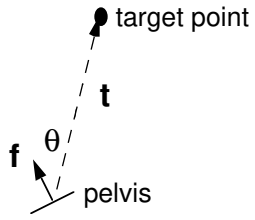
$k_{turn} > 0$ applies to the right turning perturbation and $\Delta P_{turn} = \Delta P_{turnright}$

$k_{turn} < 0$ applies to the left turning perturbation and $\Delta P_{turn} = \Delta P_{turnleft}$

and k_{turn} is computed according to the proportional control law:

$$k_{turn} = k_\theta \, \theta$$

where θ is the angle between the biped's current facing direction and a vector to the target point, as illustrated in Figure 5.10. k_θ is a gain constant which determines how tightly the biped turns for a given error in direction. k_{turn} is bounded to a predetermined maximum value in order to avoid large, unstable turn rates.



(TOP VIEW)

Figure 5.10 - Point-following. Vector f indicates the facing direction of the biped. Vector t indicates the desired direction. f and t are both in the horizontal plane.

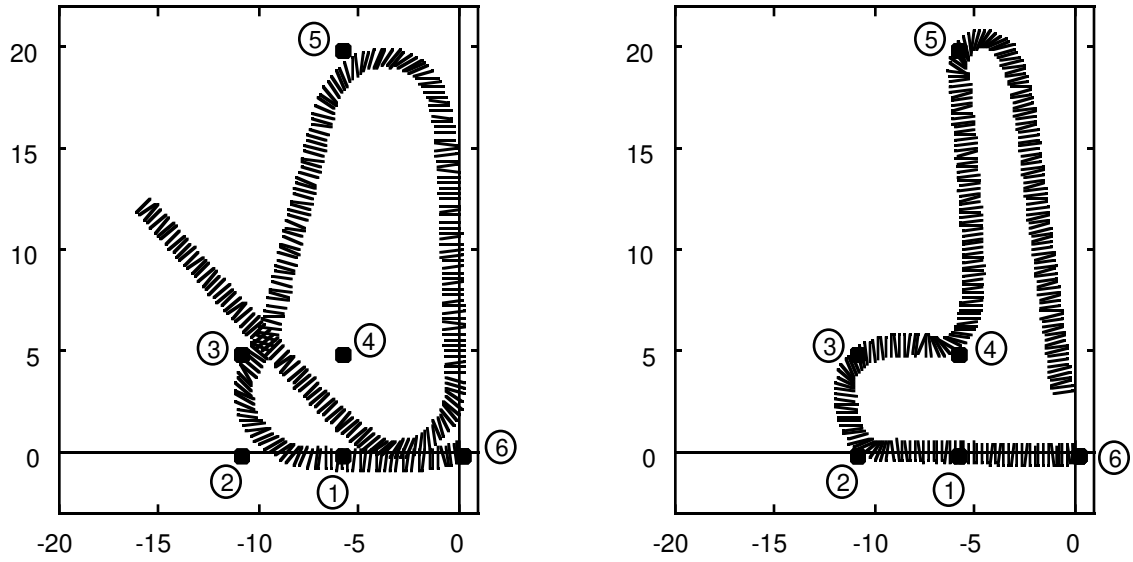


Figure 5.11 - Path following.
(a) without torso servoing
(b) with torso servoing

With this turning control, a simple form of path control can be achieved by following a suitable set of target points in sequence. Each time the biped approaches a target point to within a minimal distance, the next point in sequence becomes the current target point. Figure 5.11 shows the results of applying this algorithm to a set of target points, both with and without torso servoing. In both cases, the proportional constant, k_θ, is chosen to give the minimum radius turn when the facing direction of the biped is 45 degrees from the target point and has a maximum value at that

angle. The minimum distance to the current target point before changing to the next target point in sequence is chosen to be slightly larger than the tightest turning diameter. This helps avoid scenarios where the biped indefinitely walks in circles around a target point.

DOF:		1	2	3:0	3:1	3:2	4	5:0	5:1	6:0	6:1	6:2	7	8:0	8:1	transition info
state	S1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	S2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	.05
	S3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	.05
	S4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	S5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	.05
	S6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	.05

Figure 5.12 - $\Delta P_{striderate}$, stride rate perturbation for human model with ball-and-socket hips and arms.

5.4 Stride Rate Perturbation

The stride rate perturbation can be used to vary the stride rate of the biped. The perturbation, shown in Figure 5.12, modifies only the hold times of particular states in the base PCG. Applying the perturbation with a positive scaling parameter increases the hold time in each state, resulting in a decrease in stride rate. Applying a negative scaling parameter has the opposite effect, decreasing the hold time in each state and the increasing stride rate. The unperturbed walk is a straight walk with a stride rate of 1.0 strides/second and uses torso servoing and speed control with a composite RV[1].

Figure 5.13 (a), (b) and (c) show three distinct steps in which the perturbation is applied with a gain of –1.0, 0 and +1.0 respectively to obtain stride rates varying from 0.8 strides per second to approximately 1.25 strides per second. The three sequences are in fact taken from a single walk, during which the stride rate is dynamically varied. In this case, stride rate transitions use 3 steps for each unit of change in the perturbation gain.

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[1] In this case, an up vector-based forward RV component and a swing-COM-based lateral RV component.

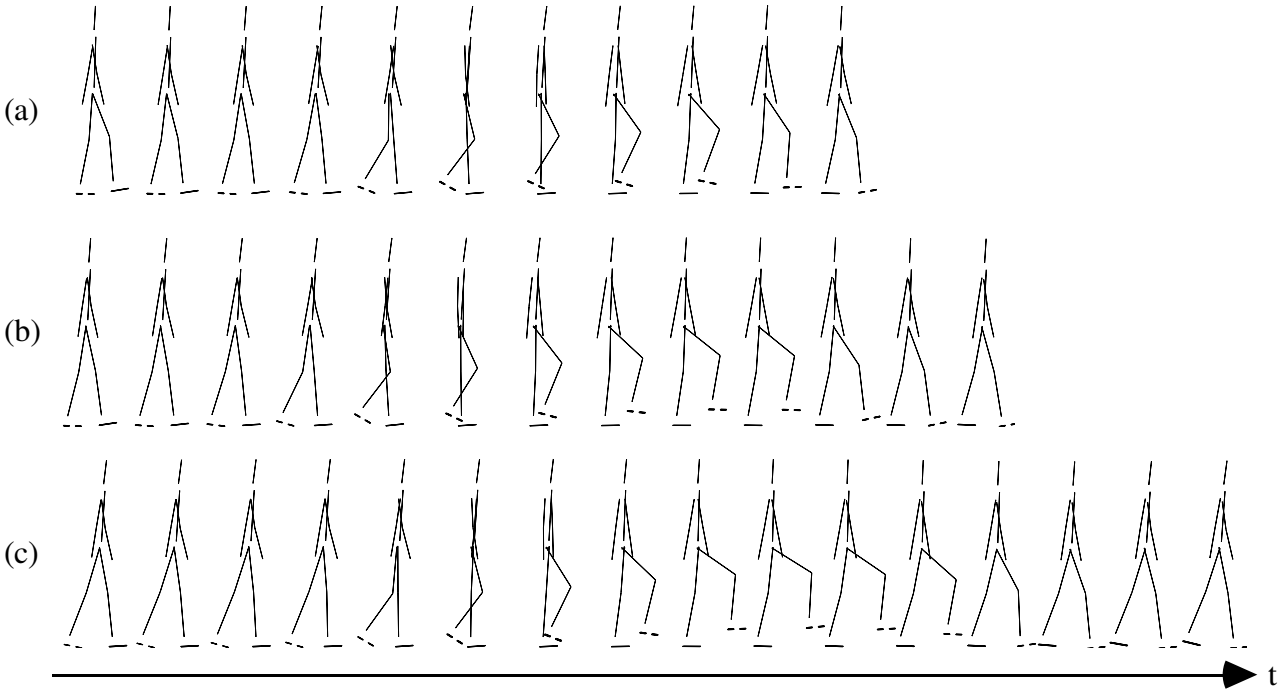

Figure 5.13 - Results of applying different stride rate perturbation scalings. Each sequence indicates one full step. Horizontal distance along the page indicates relative stride time.

(a) $k_{striderate} = -1$ i.e. $B^* = B + (-1.0 \cdot \Delta P_{striderate})$
(b) $k_{striderate} = 0$
(c) $k_{striderate} = +1$

As the sequences of Figure 5.13 indicate, the peak height of the swing knee in each step increases with hold time. This is due to an associated increase in stance hip pitch. The increased hip pitch is automatically introduced by the balance control in order to meet Q^d at the end of each step. Without this action the biped would fall due to leaning too far forward with larger hold times or too far backward with smaller hold times. The increased hip pitch gives the walk a more mechanical, "marching" appearance at lower step rates than at higher step rates.

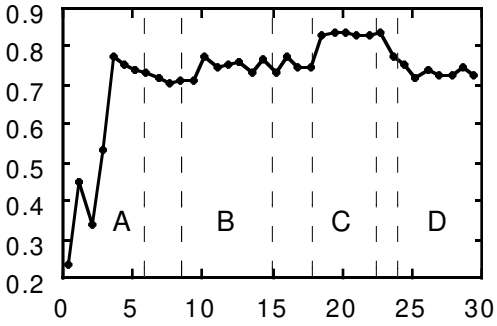

Figure 5.14 - Average speed (m/s) for varying stride rates
Region A: $k_{striderate} = 0.0$
Region B: $k_{striderate} = +1.0$
Region C: $k_{striderate} = -1.0$
Region D: $k_{striderate} = 0.0$
Other regions are transition regions.

Figure 5.14 shows the average speed of the pelvis over the course of the walk which is controlled to stay relatively constant while the biped's stride rate increases and decreases. A constant speed implies that the stride length increases inversely with stride rate (and hence linearly with hold time) for this particular perturbation.

5.5 Other Interesting Variations

PCGs varied in other ways can also be balanced successfully. Stylistic variations can be used to convey different moods or emotions and allow a broader range of abilities. In some cases, simpler variations can be combined successfully to form more complex motions. The next few sections provide some examples.

5.5.1 Bent-Knee Walking

The perturbation of Figure 5.15 generates a walk with bent knees. While this perturbation may not seem particularly useful on its own, it can be successfully combined with other perturbations to generate a ducking perturbation for the biped.

DOF:		1	2	3:0	3:1	3:2	4	5:0	5:1	6:0	6:1	6:2	7	8:0	8:1	9	10	11	12	transition info
	S1	0	0	0	-20	0	20	-20	0	0	-20	0	20	-20	0	15	-30	15	-30	0
	S2	0	0	0	-20	0	20	-20	0	0	-20	0	20	-20	0	15	-30	15	-30	0
state	S3	0	0	0	-20	0	20	-20	0	0	-20	0	20	-20	0	15	-30	15	-30	0
	S4	0	0	0	-20	0	20	-20	0	0	-20	0	20	-20	0	15	-30	15	-30	0
	S5	0	0	0	-20	0	20	-20	0	0	-20	0	20	-20	0	15	-30	15	-30	0
	S6	0	0	0	-20	0	20	-20	0	0	-20	0	20	-20	0	15	-30	15	-30	0

Figure 5.15 - Bent-knee perturbation for a human model

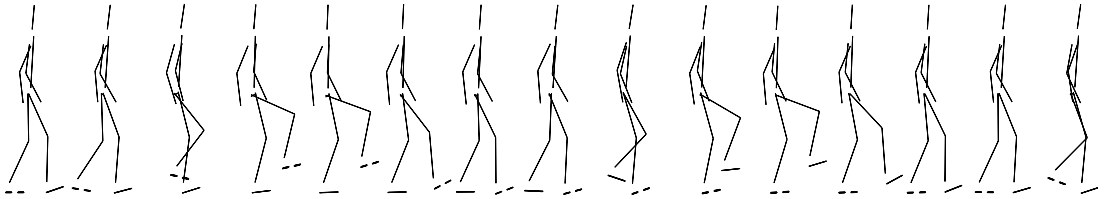

Figure 5.16 - Bent-knee walking with a parameter scaling of 1.0

Figure 5.16 shows a sequence of steps from a bent-knee walk generated by applying the perturbation to a basic forward walk. The transition from the normal walk to the fully perturbed (scaling parameter = 1.0) walk is performed smoothly over a series of 18 steps. Qualitatively speaking, the motion is lively and "bouncy". The model spends most of each stance phase standing on its heel due to a raised stance toe (-20 degrees ankle pitch).

5.5.2 Bent-Over Walking

A bent-walking perturbation shown in Figure 5.17 provides yet another walking configuration. It consists of a relatively small bend at the waist and a larger bend in the torso, generating a slightly hunched over, forward leaning walk.

DOF:		1	2	3:0	3:1	3:2	4	5:0	5:1	6:0	6:1	6:2	7	8:0	8:1	9	10	11	12	13	transition info
	S1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-52	-5	-42	-5	15	0
	S2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-52	-5	-33	-5	15	0
state	S3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-52	-5	-33	2	15	0
	S4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-42	-5	-52	-5	15	0
	S5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-33	-5	-52	-5	15	0
	S6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-33	-2	-52	-5	15	0

Figure 5.17 - Bent-over walking perturbation

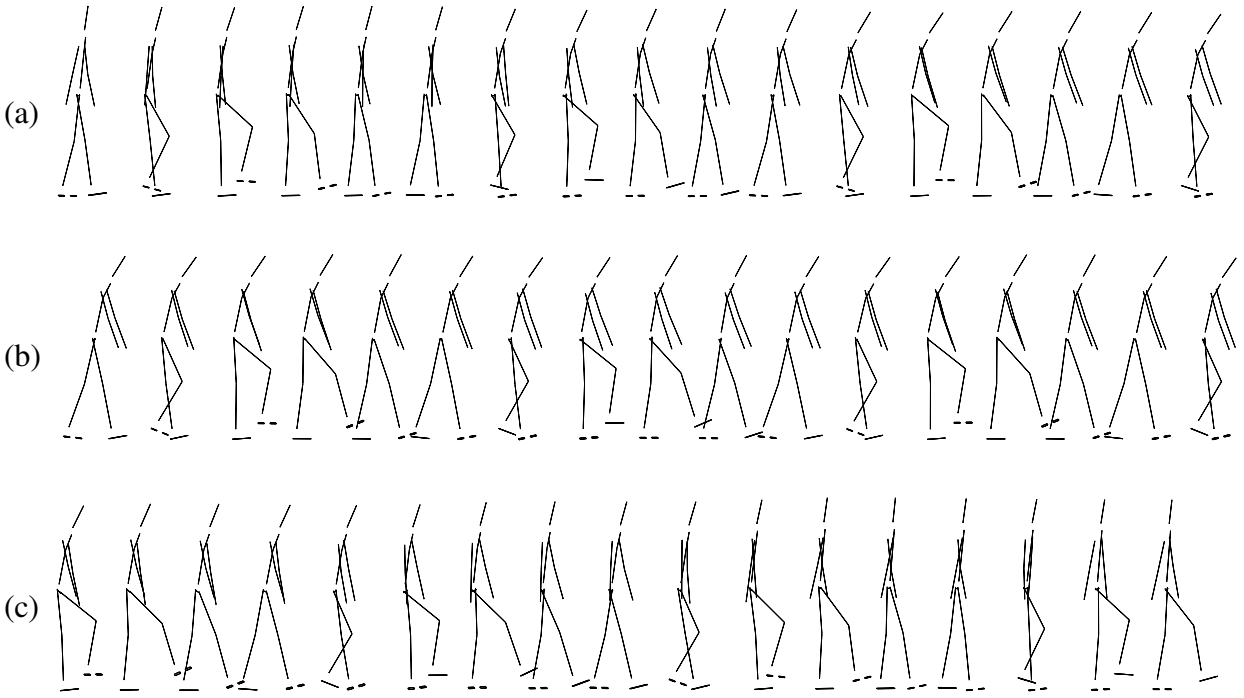

Figure 5.18 - Bent-over walking
(a) straight to bent transition
(b) walking bent-over
(c) bent to straight transition

Figure 5.18 shows the transitions into and out of the bent-over walk and a few steps of the bent-over walk. Both transitions are performed over two steps, with a different scaling parameter used for each intermediate step. The arm perturbations are included in order to make the biped's arms appear to hang by its side in a "natural" position while the body is bent-over. In retrospect, a better approach would be to reduce the stiffness and damping parameters of the shoulder actuators, letting physics determine a more appropriate arm position for the walk. This would require variable joint stiffness and damping parameters which are not currently supported.

5.5.3 Ducking

By combining the bent-knee and bent-over perturbations with an additional bend of the neck, it is possible to form a relatively simple composite "ducking" perturbation which could potentially be

used to avoid overhead obstacles. Figure 5.19 shows the composite perturbation for the human model used with the bent-over perturbation.

DOF:		1	2	3:0	3:1	3:2	4	5:0	5:1	6:0	6:1	6:2	7	8:0	8:1	9	10	11	12	13	transition info
	S1	5	40	0	-20	0	20	0	0	0	-20	0	20	0	0	-52	-5	-42	-5	15	0
	S2	5	40	0	-20	0	20	0	0	0	-20	0	20	0	0	-52	-5	-33	-5	15	0
state	S3	5	40	0	-20	0	20	0	0	0	-20	0	20	0	0	-52	-5	-33	2	15	0
	S4	5	40	0	-20	0	20	0	0	0	-20	0	20	0	0	-42	-5	-52	-5	15	0
	S5	5	40	0	-20	0	20	0	0	0	-20	0	20	0	0	-33	-5	-52	-5	15	0
	S6	5	40	0	-20	0	20	0	0	0	-20	0	20	0	0	-33	-2	-52	-5	15	0

Figure 5.19 - Composite bent-knee, bent-over and bent-neck perturbation

Figure 5.20 shows the transitions to and from "ducking". Note that while the bent-knee perturbation was originally designed for a slower rate walk which uses speed control, it also works well when applied to a different basic walk (bent-over) without speed control.

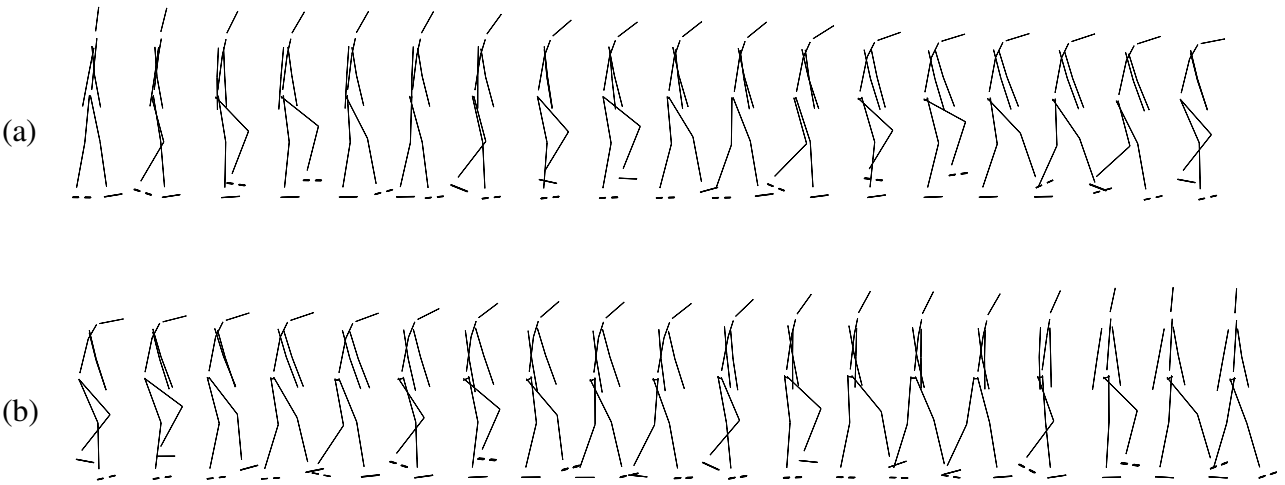

Figure 5.20 - Ducking
(a) straight to ducking transition
(b) ducking to straight transition

While the ducking perturbation is demonstrated here in an open loop configuration, one can imagine using feedback to provide the biped with the ability to automatically duck under obstacles in its path.

5.6 Conclusions

In this chapter, we have shown that parameterized PCG perturbations can be used to generate a variety of interesting gaits simply by modifying the underlying open loop control. Smooth transitions between motions were demonstrated and an example of the use of a simple feedback mechanism to increase creature autonomy was given. An approach to controlling the speed of a walk without requiring modification of the underlying base PCG was also provided. The basic balance control introduced in Chapter 3 required no modification to be used successfully with variable motions.