

# **Neurobiology of Motor Control**

Fundamental Concepts and New Directions

*Edited by*

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## 9

## Sensory Feedback in the Control of Posture and Locomotion

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### 9.1 Introduction

All animals must find food, avoid predation, and reproduce. Living on land adds the additional challenges of gravity and functioning at the interface between a low-drag atmosphere and a textured substrate. Friction must be minimized to move quickly over this substrate, which can be accomplished by having a polarized, axial body structure raised on segmentally specialized, jointed legs. This set of adaptations was achieved by both vertebrates and invertebrate arthropods, including insects, crustaceans, and arachnids.

Legged animals face the additional challenges of maintaining body posture against gravity and external perturbations both when stationary and when moving. The common body plan presents common control problems to both sets of animals: how to produce stable postures, how to produce coordinated and stable locomotor gaits, and how to shift efficiently between these states in a noisy, changing environment. These common control problems have led to common solutions. In both sets of animals descending motor commands excite similar motor circuits to produce similar leg and body movements. Feedback from similar sensors then provides information on the immediate consequences of the motor commands, which is particularly important in shaping their postural and locomotor behaviors. These common solutions have emerged despite large differences in the sizes, skeletal structures, and habitats of vertebrates and arthropods. In the last 50 years, human engineers have discovered the same strategies in their efforts to build devices that respond adaptively to the environment.

*Chapter Plan* We begin with a brief history of feedback control and a review of classical control theory. We then show how that theory informs our general understanding of the control of limb movement and posture. We then describe feedback control of posture and locomotion in arthropods and vertebrates, and interpret that in light of control theory. We end with a discussion of promising future research strategies.

## 9.2 History and Background of Feedback Control

Negative feedback first came into widespread use in fly-ball centrifugal governors that controlled the rotation speed of early steam engines (Maxwell 1868). As engine speed increased, the plane of the fly-ball rotation rose and reduced the flow of the steam that drove the engine. The valve openings and sensitivity of the system could be adjusted to enable it to rotate at a near constant speed independent of steam pressure.

In the mid-19<sup>th</sup> century, Claude Bernard identified negative feedback as being responsible for maintaining the constancy of the internal body environment despite changes in outside conditions (Gross 1998). Early in the 20<sup>th</sup> century, Charles Sherrington showed how spinal reflexes used negative feedback to resist perturbations to maintain limb positions and body postures (Sherrington 1910). He showed that the reflex response consisted of several parallel pathways that excited ipsilateral muscles to resist the perturbation and inhibited their antagonists, while also exciting and inhibiting appropriate contralateral muscles to maintain body posture.

Sherrington also showed how these reflexes could be chained in sequences to generate rhythmic locomotor movements (Sherrington 1913). An initial leg movement would trigger a reflex response in the opposing direction, and the resulting movement would trigger another reflex response in the original direction. While working in Sherrington's laboratory, Brown showed that "central pattern generators," as they later came to be known, were the primary drivers of rhythmic motor activity in cat spinal cord (Brown 1911; Stuart and Hultborn 2008) (see also Chapter 8). Recent work in many animals has established the importance of feedback-evoked reflex responses in helping centrally generated rhythmic motor patterns adjust to the physical demands of locomotion (Duysens et al. 2000).

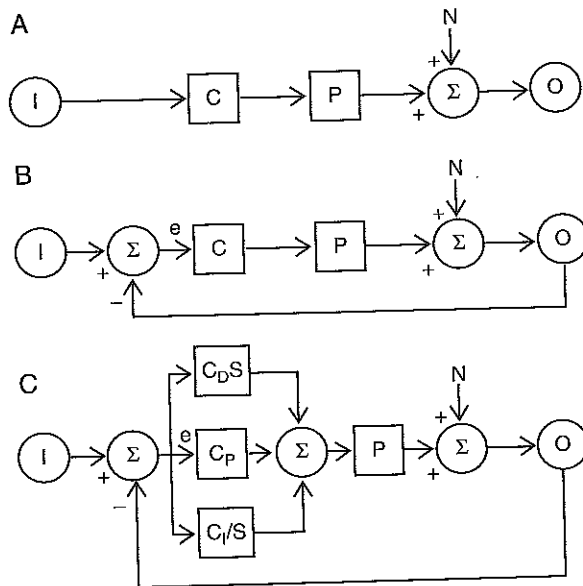
The development of radar during World War II made it possible to couple sensing the position and velocity of an enemy aircraft with directing and firing an anti-aircraft gun. Work on this problem led to the development of what is now called "classical" control theory, which showed how desired patterns of output could be evoked from any system in a noisy environment despite large differences between the power of the control signal and that of the output. In his book "Cybernetics: Command and Control in the Animal and the Machine," Wiener (1961) showed that the same control problems are faced by animals.

## 9.3 Classical Control Theory

Figure 9.1 shows how negative feedback enables a weak input signal to control the output of a much more powerful system in the presence of noise.  $I$  is the input to a system, e.g., the angle of a steering wheel, and  $O$  is the output, e.g., the angular direction of a large ship (these are Laplace variables that lend themselves to mathematical descriptions of negative feedback systems and provide a means of predicting how they behave). The power required to change the angle of the ship is much greater than the power needed to turn the steering wheel, and thus the steering wheel signal,  $I$ , must be amplified greatly. This is accomplished by a controller,  $C$ , and steering plant,  $P$ .

Ship direction can be affected by external stimuli, or noise,  $N$ , such as a cross-wind perpendicular to the ship's direction, which can be much larger than the input signal,  $I$ .

**Figure 9.1** Control systems without and with feedback. (A) Without feedback.  $I$  is input,  $O$  output,  $C$  the controller,  $P$  the plant, and  $N$  noise. Arrows pointing to a rectangle are its inputs. Arrow leaving a rectangle is its output, the product of the rectangle and its input. Output of a summing node (a circle with a "Σ") is the sum of its inputs, according to the sign adjacent to the input arrow. (B) A proportional controller,  $e$  is error. (C) A PID controller, where  $s$  is the Laplace frequency variable, and  $C_D$ ,  $C_P$ , and  $C_I$  are the differential, proportional, and integral control gains, respectively.



Without feedback, the output is given by

$$O = N + ICP, \tag{9.1}$$

so that the ship's direction depends directly on the noise  $N$  and the input amplified by the controller and the plant,  $ICP$  (Fig. 9.1A). If the noise is comparable in amplitude to  $ICP$ , the output  $O$  will be significantly distorted. However, if the output  $O$  (the ship's angular direction) is "fed back" to the input and subtracted from it (Fig. 9.1B), the effect of noise is greatly reduced. The difference between input and output is the error,  $e$ , in the output of the system,

$$e = (I - O). \tag{9.2}$$

If the error is amplified by the controller,  $C$ , and by the plant,  $P$ , the product is the output,  $O$ :

$$O = eCP = (I - O)CP. \tag{9.3}$$

Because the output is modified by noise,  $N$ , the complete expression becomes

$$O = N + (I - O)CP, \tag{9.4}$$

which can be re-arranged to

$$O = (N + ICP)/(1 + CP). \tag{9.5}$$

If  $CP \gg N$  and  $\gg 1$ , then  $O \sim I$ . This means that despite perturbations produced by noise, system output will equal system input. This is very useful in many systems, such as that described here; feedback allows the ship to be steered in the desired direction despite powerful perturbations.



**Delay** The negative feedback system in equation 9.5 assumes that the feedback is effectively instantaneous relative to the rate of change of any system variable, including input, output, and noise. When this is not true, interesting (and occasionally catastrophic) things can happen. Assume, for instance, that it takes some time,  $\tau$ , for the input to activate the plant and generate an output, but that the feedback from that output is immediately subtracted from the input. If the input varies with a period twice the time needed to produce the output, then an output peak will produce a peak in feedback that is subtracted from the input at a time when the input is in a trough. As a result, the delay has transformed the negative feedback into positive feedback, where the error signal grows with each cycle of the feedback loop.

The frequency where the system blows up is  $f_{\infty} = 1/2\tau$ . Longer delays thus cause the system to blow up at lower input frequencies. The best way to expand the range of input frequencies over which the system operates without blowing up is to minimize the delay; for many systems the delay can be reduced enough so that  $f_{\infty}$  is outside the frequency range of normal inputs. However, sometimes there is a limit to how fast the output can be produced in response to an input. In animals, for instance, the delay in responding to a motor command results from the time needed for excitation–contraction coupling, for muscle contraction, and to overcome limb and load inertia. These times can be substantial. In cats the shortest delay of the ankle muscle monosynaptic stretch reflex is about 12 ms, in humans about 30 ms. Unaided, this system will blow up if the frequencies of the input to the motoneurons are near  $f_{\infty}$ , 42 Hz for cats and 17 Hz for humans. However, there is also an instantaneous negative feedback to postural perturbations caused by intrinsic muscle properties—so-called short-range muscle stiffness—in which muscle stretch increases muscle force. This response is not mediated by sensory afferents. This instantaneous negative feedback can be made to work for both flexing and extending perturbations by co-contracting opposing muscles.

**PID Controllers** The feedback systems described above use a signal proportional to the response error,  $e$ , to drive the plant:

$$\text{Plant input} = Ce = C(I - O). \quad (9.6)$$

For systems functioning in rapidly changing environments, this mechanism may be inadequate to prevent the error from becoming disastrously large. It may also leave a residual difference between input and output after steady-state is achieved. The residual error may be both large enough to impair system effectiveness and too small for the feedback to reduce further.

These problems can be addressed by adding an additional pair of controllers, one that responds to the rate of change of the error and one that responds to its time integral, to create a proportional-integral-derivative (PID) controller (Fig. 9.1C). In this scheme, the plant,  $P$ , is driven by three controllers,  $C_p$ ,  $C_I$ , and  $C_D$ , that respond to the amount of error ( $C_p$ ), the time-integral of the error ( $C_I$ ), and the rate of change of the error ( $C_D$ ). The response of the controller becomes

$$C(t) = \left( e(t)C_p + \int_0^t e(t)C_I dt + \left( \frac{de}{dt} \right) C_D \right). \quad (9.7)$$

The Laplace transform yields an algebraic formula that can be used to revise equation 9.7:

$$O = \left[ N + I \left( C_p + \frac{C_I}{s} + sC_D \right) P \right] / \left[ 1 + \left( C_p + \frac{C_I}{s} + sC_D \right) P \right], \quad (9.8)$$

where  $s$  is the frequency variable in the Laplace domain. For low values of  $s$  (low frequencies),  $PC_I/s$  is large compared to both  $P(C_p + sC_D)$  and  $N$ , and thus  $O \sim I$ . For high values of  $s$  (high frequencies)  $PsC_D$  is large relative to  $P(C_p + C_I/s)$  and to  $N$ , and so again  $O \sim I$ . In the middle range of frequencies,  $C_pP$  is large compared to  $P(sC_D + C_I/s)$  and to  $N$  and  $O \sim I$  as in equation 9.5.

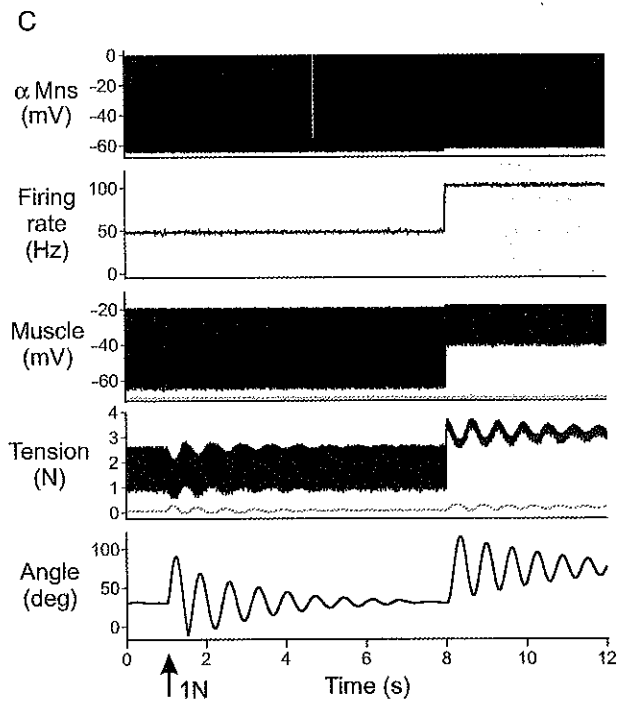
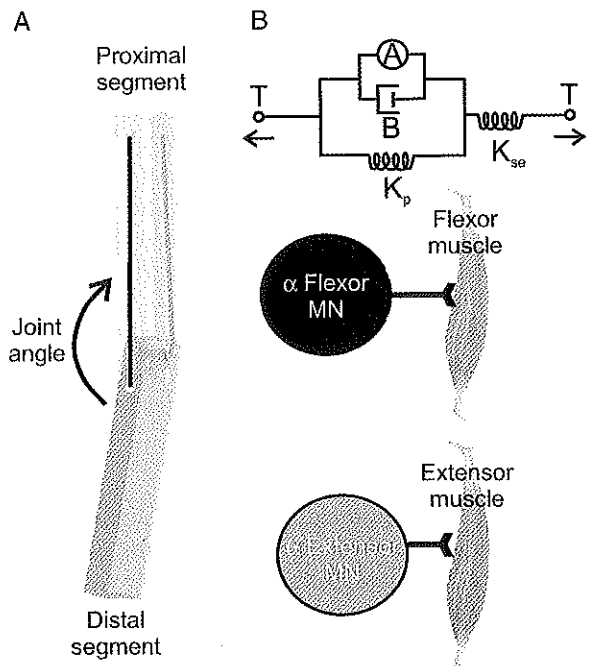
## 9.4 Nervous System Implementation in the Control of Posture and Limb Movements

Feedback systems that conform to the formal description given above are implemented by the nervous system at several levels to help control movement, beginning with control of limb movement around a single joint. To illustrate this, we used the neuromechanical simulator AnimatLab (Cofer et al. 2010a; see [www.animatlab.com](http://www.animatlab.com)) to create a single jointed limb model (Fig. 9.2A), in which flexor (black) and extensor (gray) muscles stretch across opposing sides of a hinge (elbow or knee) joint to flex and extend a distal limb segment. The flexor and extensor muscles are Hill type models consisting of a spring in series with a parallel combination of a spring, a dashpot, and an actuator that transduces membrane depolarization into contraction force (Fig. 9.2B). The muscles are excited by integrate-and-fire motoneurons (MN).

Without feedback (Fig. 9.2C), tonic current stimulation of the  $\alpha$  Flexor MN sufficient to make it fire at 50 Hz flexed the resting limb against the forces of gravity and the stretching extensor muscle. The flexor EPSPs produced an oscillating flexor muscle membrane potential and a flexor muscle tension that varied around a mean of just less than 2 N. These oscillations are greater than would be observed in real limbs because the muscle models each have the same single time-constant and are each excited by single motoneurons. Despite these oscillations, the motoneuron activity produced a steady 30° flexion of the limb.

*Response to Limb Perturbation without Feedback* Limb posture was disturbed by an upward 1N force applied for 100 ms to the distal limb segment at 1 s (arrow, Fig. 9.2C). The perturbation evoked a large, very slowly decaying oscillation of the distal limb segment. This oscillation, and that described in the next paragraph, resulted from the spring-like nature of the flexor and extensor muscles and the pendular arrangement of the joint and distal limb.

*Response to Step Excitation of the  $\alpha$  Flexor MN Without Feedback* A step depolarization was then applied to increase  $\alpha$  Flexor MN firing rate to 100 Hz (time = 8 s, Fig. 9.2C). Flexor potential and tension increased, causing the distal limb segment to flex quickly. An oscillation was again evoked that only very slowly declined to the new limb flexion angle (full decay not shown).





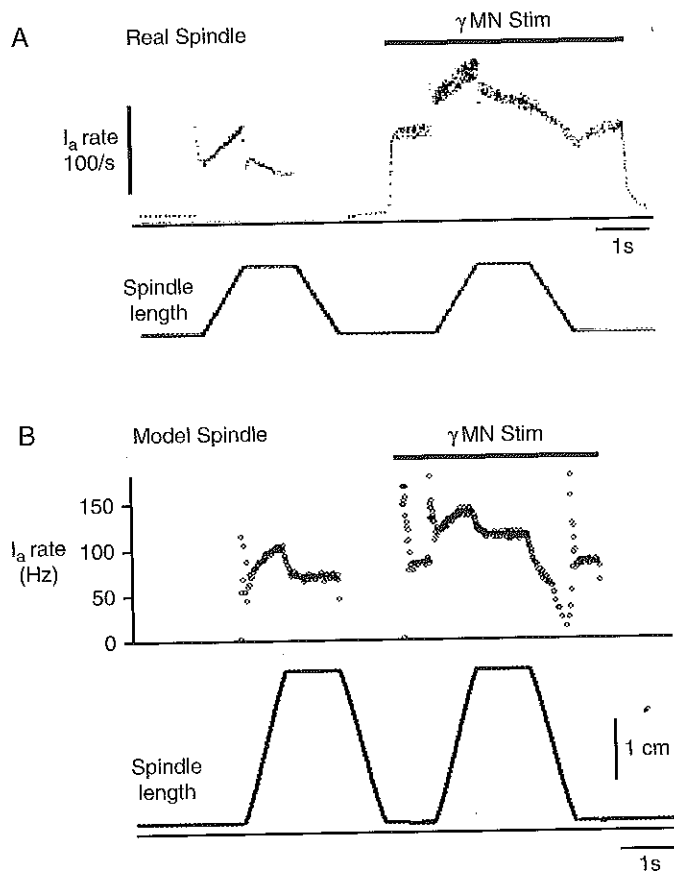
**Figure 9.2** A neuromechanical single joint limb model. (A) The limb consisted of a fixed Proximal Segment connected by a hinge joint to a Distal Segment. Flexor (black) and Extensor (gray) muscles span the anterior and posterior sides, respectively, of the joint. (B) Top: Hill muscle model, with a parallel spring (spring constant,  $K_p$ ), serial spring (spring constant,  $K_{se}$ ), dashpot (dashpot constant,  $B$ ), and actuator,  $A$ .  $T$  is tension developed across the model. Bottom: Integrate and fire models of single  $\alpha$  Flexor and  $\alpha$  Extensor MNs drive the Flexor and Extensor Muscles. (C) Model activity. Black and gray traces show flexor and extensor activity, respectively. 1<sup>st</sup> trace:  $\alpha$  MN membrane potential; 2<sup>nd</sup>:  $\alpha$  MN firing rate; 3<sup>rd</sup>: muscle membrane potential; 4<sup>th</sup>: muscle tension; 5<sup>th</sup>: joint angle. Stimuli: A 30° limb flexion was maintained at the outset by a constant +12 nA injected in the  $\alpha$  Flexor MN. At 1 s (arrow) the joint was perturbed by a 1 N, 0.1 s upward force applied to the distal limb segment. At 8 s, an additional +20 nA current step was injected into the  $\alpha$  Flexor MN to increase limb flexion. Note oscillations with perturbation and changes in MN firing rate.

*Sensors for Feedback: Muscle Spindles and Muscle Receptor Organs* Vertebrate muscle spindles and arthropod muscle receptor organs consist of small groups of muscle fibers that lie parallel to the muscle they help control. Both include terminals of motoneurons that innervate them, and stretch-sensitive endings of afferents that respond to stretch or active contraction of the sense organ. In the spindle, stretch or contraction of a nuclear bag fiber (one of two types of spindle muscle fibers) excites Ia afferents. In cat, Ia afferents respond phasically to the onset of spindle stretch, increase their firing rate linearly with increasing stretch, and drop to a lower rate when stretch is maintained (Fig. 9.3A, left) (Prochazka 1996). The phasic and linear responses provide the derivative and proportional feedback used in a PD controller (Fig. 9.1). Stimulation of one of the  $\gamma$  motoneurons that excite the spindle evokes a phasic Ia response at stimulation onset and a sustained response with maintained  $\gamma$  MN stimulation (Fig. 9.3A, right). Spindle stretch during  $\gamma$  MN stimulation evokes enhanced Ia responses.

To illustrate how spindles help control joint movement, we placed flexor and extensor muscle spindles in parallel with the flexor and extensor muscles in the limb model (see Fig. 9.4). Each spindle had the same origin and insertion attachments to the limb as its corresponding muscle. The spindle model is a Hill model that, like the muscle model, represents spindle elastic, viscous, and force-generating properties (Fig. 9.2B). Because the spindle contains many fewer muscle fibers than the main muscle, the spring constants of the spindle model were reduced to 10%, and the dashpot constant was reduced to 75%, of the corresponding muscle model values. The model spindle transduces spindle tension and the serial spring's rate of stretch to generator currents that are applied to an integrate and fire model of an Ia afferent. Parameter values of the spindle and Ia afferent were set to make afferent responses to imposed stretch very similar to real responses of cat Ia afferents both with and without Ia firing (compare Fig. 9.3A and B).

*Adding Negative Feedback from Muscle Spindles to Control Movement* Flexor and extensor feedback loops were enabled by having the flexor and extensor Ia afferents synaptically excite the  $\alpha$  Flexor and Extensor MNs (Fig. 9.4A). Flexor and Extensor Spindles were excited separately from Flexor and Extensor Muscles by the  $\gamma$  Flexor and Extensor MNs. In addition, cross-inhibitor interneurons prevented excitation of antagonist MNs. These are negative feedback loops because the muscle contraction each MN produces reduces tension in the associated spindle, and so reduces the excitation of the Ia afferent that excites the MN.

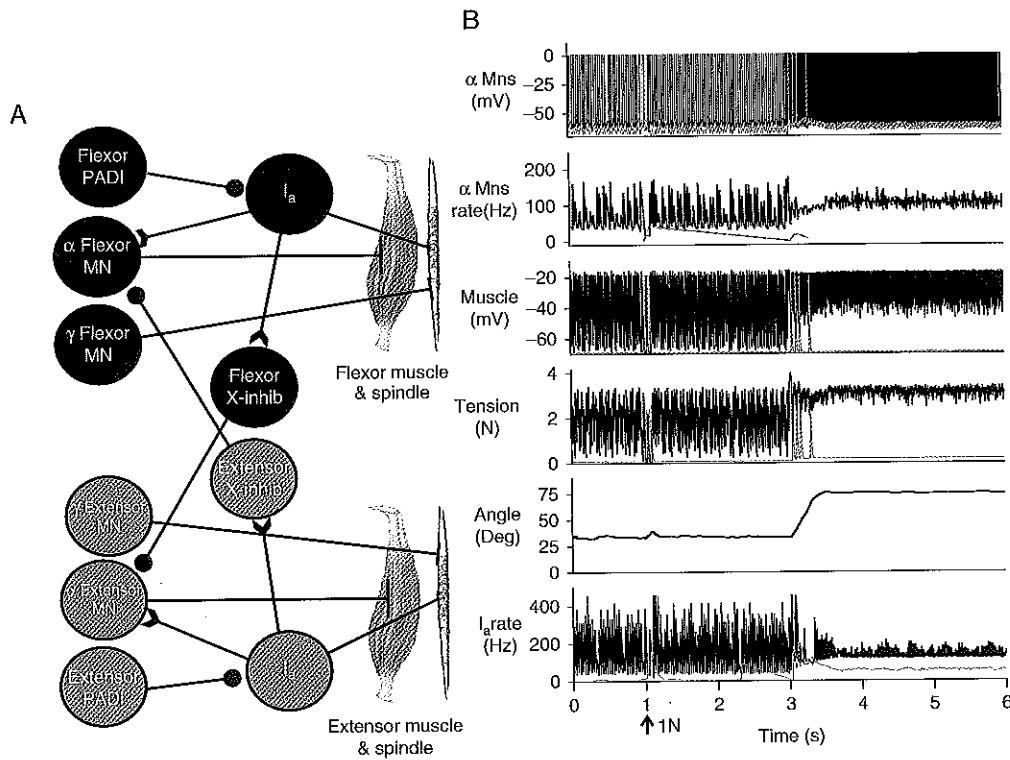




**Figure 9.3** Ia responses to stretch of real and model spindles. (A) Ia firing rate responses (top) to stretch (bottom) of a mammalian spindle before (left) and during (right)  $\gamma$  MN stimulation. Modified from Prochazka (1996). (B) Model Ia firing rate responses (top) to stretch (bottom) of a model spindle before (left) and during (right)  $\gamma$  MN stimulation.

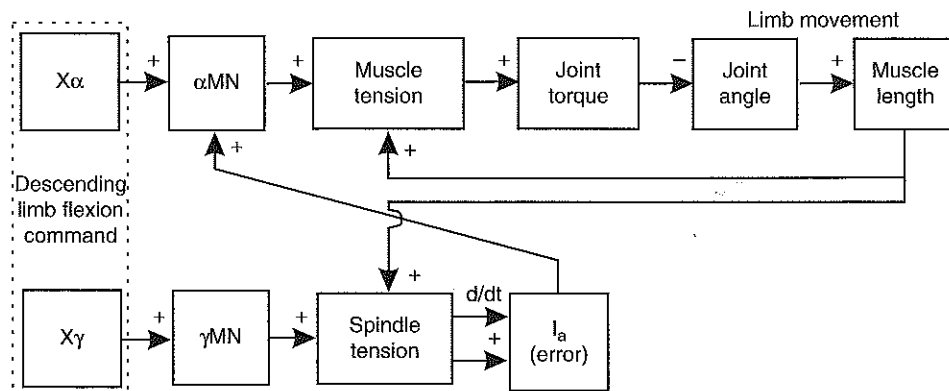
**Resistance Reflex Responses to External Perturbation** A constant stimulus was applied to the  $\alpha$  Flexor MN so as to induce an initial joint angle of about  $33^\circ$ . The same upward, 1 N force was applied at 1 s to cause limb flexion. This upward movement stretched the extensor spindle and phasically excited the extensor Ia afferent, which in turn excited the  $\alpha$  Extensor MN and inhibited the  $\alpha$  Flexor MN. These responses dramatically reduced the initial flexion induced by the perturbation (compare to Fig. 9.2C). As the limb fell back, a similar extension reflex response prevented oscillation and brought the limb position to equilibrium within 200 ms. This postural control system functions like a PD controller. The afferent response is the error signal, and is proportional to both the amount of spindle tension and its rate of change (Fig. 9.3B, left).

**Feedback Control of Voluntary Movement** When the  $\alpha$  and  $\gamma$  Flexor MNs were simultaneously depolarized by injected current (time = 3 s, Fig. 9.4B), the  $\alpha$  Flexor MN responded with a step increase in firing that was immediately augmented by a burst of Flexor Ia



**Figure 9.4** Neuromechanical single joint limb model with feedback control. (A) Model in Fig. 9.2 with  $\gamma$  Flexor and  $\gamma$  Extensor MNs, Flexor and Extensor PADI Interneurons (PADI), Flexor and Extensor  $I_a$  afferents, Flexor and Extensor X-inhib (cross-inhibitory) interneurons, and Flexor and Extensor Muscle Spindles (Fig. 9.3B). (B) Flexor  $\alpha$  and  $\gamma$  MNs were each initially excited by constant injected current (4 nA and 8 nA, respectively) to maintain limb flexion at 30° against gravity and extensor tension. At 1 s (arrow), a 1 N, 0.1 s vertical force was applied to the distal segment. At 3 s, the current stimuli to the  $\alpha$  and  $\gamma$  Flexor MNs were increased by 15 nA and 20 nA, respectively. The Extensor PADI was excited by 1 nA from 5.145 s to 5.33 s. 1<sup>st</sup> trace:  $\alpha$  MN membrane potential; 2<sup>nd</sup>:  $\alpha$  MN firing rate; 3<sup>rd</sup>: muscle membrane potential; 4<sup>th</sup>: muscle tension; 5<sup>th</sup>: joint angle; 6<sup>th</sup>:  $I_a$  afferent firing rate. Flexor element responses are in black; extensor element responses are in gray. Note the lack of oscillation of the joint angle after perturbation and the smooth trajectory to a new limb position following the change in MN firing rate.

activity. The Flexor  $I_a$  burst was evoked by the sudden increase in Flexor Spindle tension produced by the step activation of the Flexor  $\gamma$  MN. The spindle contracted isometrically because the limb had yet to move, and as a result spindle tension increased suddenly. The  $\alpha$  Flexor MN burst provided a transient increase in flexor tension that helped initial joint flexion. Joint flexion stretched the Extensor Spindle and excited the Extensor  $I_a$  afferent. The Extensor  $I_a$  excited the  $\alpha$  Extensor MN, which slowed the rate of flexion. The timing and amplitudes of afferent and motorneuron responses were such that limb flexion drove smoothly to the desired equilibrium angle, thus again removing the oscillation seen without feedback. After the initial flexion, the crossed inhibitory IN (Fig. 9.4A) prevented the Extensor MN from responding to the Extensor  $I_a$  even though it was continuously excited after the limb reached its new position. The  $\alpha$  Flexor MN



**Figure 9.5** Flow chart of  $\alpha/\gamma$  feedback loops. Positive and negative signs indicate whether the influence is in the same or opposite direction. Note that the sign reversal, where increased joint torque decreases joint angle, participates in two negative feedback loops, one mediated by increased muscle stiffness, the other by the spindle Ia afferent.

was thus unopposed after the transient responses of the  $\alpha$  Extensor MN, and steady state joint flexion was set solely by flexor muscle contraction and limb weight.

Although the Ia afferents provide feedback in the limb position control system, how that system maps onto the negative feedback system shown in Fig. 9.1 is not straightforward. It may initially seem that the Ia response is a negative feedback signal and the error is calculated in the central nervous system. However, the error is actually calculated peripherally from the tensions in both the working muscle and the muscle spindle. This is apparent if we examine the control system for one muscle type (flexor or extensor) (Fig. 9.5). Motor control is shared by both the  $\alpha$  and  $\gamma$  MNs, where  $X_\alpha$ , the alpha command, provides a baseline for the control system to operate on, and  $X_\gamma$ , the gamma command, is the control command. Increased  $\alpha$  MN activity increases muscle tension and joint angle torque, which reduces muscle and muscle spindle lengths. This sign inversion makes the feedback negative. The reduced muscle length immediately reduces muscle tension, and so creates the instantaneous negative feedback loop described earlier that depends on intrinsic, short range muscle stiffness. In this loop muscle tension is the error signal, subtracting the effects of muscle shortening from the effects of  $\alpha$  MN excitation. Spindle tension similarly results from the difference between the effects of  $\gamma$  MN activity and of muscle length, which varies with limb position. In this loop, spindle tension is the error signal and produces the generator current for the Ia afferent. The afferent responds to both spindle tension and its rate of increase, and its response adds to the excitation of the  $\alpha$  Flexor MN.

**PAD Inhibition of the Antagonist Ia Response** Negative feedback (resistance) reflexes stabilize limb position and so can interfere with voluntary movements. To block unwanted feedback at the time of the expected reflex response, movement commands therefore also excite neurons that inhibit spindle afferents. In the spinal cord of vertebrates and the ventral nerve cord of crustaceans, pre-synaptic inhibition in the form of primary afferent depolarization (PAD) prevents afferents from reflexively exciting antagonist MNs that would oppose the voluntary movement (Clarac 2008). As in the vertebrate myotactic



reflex explained above, PAD is invoked in crustaceans during walking to prevent resistance reflexes from interfering with walking movements. Indeed, the resistance reflexes are transformed into assistance reflexes, in which the agonist MN is excited to enhance the movement that triggered the reflex (Cattaert and Le Ray 2001). This sort of reflex reversal also occurs in vertebrates (Ekeberg and Pearson 2005).

In the limb flexion model, the Extensor PAD Inhibitory interneuron (PADI) inhibited the Extensor Ia afferent (Fig. 9.4A). The Extensor PADI was depolarized with a brief (185 ms) current pulse at the onset of Flexor MN stimulation. The resulting inhibition shortened and reduced Extensor Ia response and allowed the limb to flex nearly to its target position before extensor tension and Flexor MN inhibition slowed it and brought it to rest (Fig. 9.4B). The flexion response was truly tri-phasic: an initial, strong Flexor MN excitation, a subsequent dip in Flexor MN response and a burst in the Extensor MN, and finally a sustained Flexor MN discharge.

*Role in Postural Control* Animal posture consists of a set of joint angles the limbs adopt. For each joint, any particular angle can be achieved with a range of opposing muscle excitations, each of which changes joint stiffness. Increased tension in the opposing muscles increases the gain of the instantaneous feedback described above, and thus makes the limb more resistant to perturbation. Varying  $\gamma$  MN excitation to muscle spindles changes spindle tension and thus the gain of the Ia feedback loop, and hence also changes resistance to perturbation.

*Role in Movement Commands* Feedback allows  $\alpha/\gamma$  co-activation step commands to produce step-like limb flexions (Fig. 9.4B). Additional simulations demonstrate that flexion movement scales nearly linearly with step command and will follow a sinusoidal command, diminishing in amplitude with command frequency, like a low-pass filter. Thus, despite the complexities of muscle contraction and perturbation by external forces, feedback, including  $\gamma$  modulation of the feedback and PAD inhibition of unwanted feedback, enables relatively simple motor commands to produce proportional limb movements around a joint.

*Load Compensation and Gain* If the gain of the loop is sufficiently large, feedback can enable a limb to produce the same movement under increased loads. The loads can be represented by the noise term,  $N$  in (5), so minimizing their effect requires that the product  $CP$ , the open loop gain, is large compared to  $N$ . If it is not, then the error will increase and limb flexion will fall short of the target by an amount proportional to the load and inversely proportional to the gain. Better compensation occurs when gain is increased, but that risks making the system unstable.

*Positive Feedback* Negative feedback becomes positive when the feedback is added to, rather than subtracted from, the input, so that "error" growth accelerates. The resulting explosive growth of output can produce useful power surges and rapid state transitions, but, to be useful, these rapid changes must be controlled. Positive feedback is often controlled by nesting it within a larger negative feedback system that limits total change. For example, the rapid membrane depolarization of an action potential is produced by the positive feedback between depolarization and sodium channel opening. The membrane depolarization is limited by the sodium equilibrium potential ( $E_{Na}$ ), because inward



sodium current is proportional to the difference between membrane potential and  $E_{Na}$  (see Chapter 2). In locomotion, positive feedback assistance reflexes promote rapid transitions between stance and swing that are stabilized by negative feedback. At the end of stance, a leg perturbation or an attempt to lift it may trigger an assistance reflex that excites leg flexor motor neurons. The assistance reflex may increase as the leg rises and be extinguished as the leg reaches the limits of elevation (Chung et al. 2015).

## 9.5 Organization and Function in Arthropods

Arthropods engage in complex and sophisticated movements. A cockroach walking at high speed over a rough terrain, crayfish wrestling for social dominance, and a praying mantis carefully stalking its prey before launching a directed attack, all require a high degree of coordination between brain centers, thoracic motor centers, and multiple streams of sensory feedback continuously arriving from the periphery. Posture and locomotion are controlled in arthropods using sensory feedback from a wide variety of sensors and musculoskeletal structures and the control principles and organizational patterns described above. Arthropod bodies, limbs, and nervous systems have been widely reviewed (Burrows 1996; Derby and Thiel 2014; Niven et al. 2008; Strausfeld 2012; Watling and Thiel 2013). We therefore here provide only a brief summary to acquaint readers unfamiliar with the general organization.

### 9.5.1 Locomotory System Gross Anatomy

Like a suit of armor, the arthropod exoskeleton provides a protective hard cuticular surface for the limb or body segment with a flexible soft cuticular covering at each joint. Muscles originate from interior points of the exoskeleton and project across a joint to attach on the cuticle or an apodeme, an internal tendon-like structure. Insect and crustacean legs are segmented tubular structures that emerge from the thorax, itself a fused multi-segmental structure. The legs contain five (insects) or seven (decapod crustaceans) serially arranged segments, ending with single or paired (pincer) claws. The leg segments are linked together by bicondylar hinge joints that allow the claw to move through a wide range of the space around the body. The joints have wide angles of movement and are generally oriented orthogonal to each other: the proximal, thoracic-coxa (TC) joint moves the entire leg forward and back; the adjacent joint (coxobasal (CB) in Crustacea, coxa-trochanter (CT) in insects) levates and depresses the leg; the next major joint (carpus-propodus (CP) in Crustacea, femur-tibia (FT) in insects) flexes and extends the distal portion of the leg.

### 9.5.2 Proprioceptors and Exteroceptors

The legs contain multiple proprioceptors and exteroceptors that provide sensory feedback to the nervous system (Mill 1976). Like muscle spindles, muscle receptor organs (MROs) are clusters of muscle fibers with embedded stretch receptors that give rise to length-sensitive sensory afferents (DiCaprio and Clarac 1983). Like spindles, they receive efferent innervation that enables them to play a similar role in feedback control (Head and Bush 1991). Chordotonal organs (CO) are elastic strands with embedded sensory afferents but no efferent supply. The afferents respond to CO stretch

and release as the joint opens and closes. Tendon receptors, like Golgi tendon organs, respond to apodeme force (Hartman 1985). Cuticular sensors, campaniform sensilla (CS) in insects (Zill et al. 2010; Zill and Moran 1981), and cuticular strain detectors (CSD) (Klarner and Barth 1986) and funnel canal organs (FCO) in crustaceans (Liberat et al. 1987a), respond to forces produced in the leg cuticle by muscle contraction or leg torque. Hair-like receptors respond to contact with the ground, with another body segment at a joint, or with an external object or force on the leg.

### 9.5.3 Arthropod Nervous Systems

Arthropod nervous systems are ladder-like structures segmentally organized (see also Fig. 10.2) into ganglia connected by paired intersegmental connectives, which are bundles of axons. Each bilaterally symmetric thoracic ganglion controls a pair of legs and contains about 2,000 neurons, 1,900 of which are interneurons (Wiersma 1961). Sensory afferents project to their segmental hemi-ganglion and motorneurons project to their segmental muscles. While the distal portion of the leg is supplied by hundreds of sensory afferents from cuticular hairs (Marchand et al. 1997), several other sense organs contain small numbers of sensory afferents, some of which are individually identifiable or as one of an identifiable small group (Cattaert 2014). Even fewer motorneurons innervate the legs; each walking leg of a lobster or crayfish is innervated by approximately 95 motorneurons, nearly all of which are individually identifiable (Chrachri and Clarac 1989). Unlike vertebrates, arthropods possess inhibitory motorneurons that prevent excitation of a muscle or speed muscle relaxation (Govind and Atwood 1982). One inhibitory motorneuron, the common inhibitor, innervates all the muscles of a leg.

### 9.5.4 Postures and Movement Commands (see also Chapter 7.3)

Postural and locomotor movements are initiated by descending commands from anterior parts of the nervous system. In Crustacea, a variety of static postures and locomotor movements can be released by stimulating discrete “command fibers” in the circumesophageal connectives that link the brain and ventral nerve cord (Bowerman and Larimer 1974a,b; Evoy and Ayers 1982). Neurons in the central complex of the insect brain are important for decisions related to walking speed and movement around barriers (Bender et al. 2010; Ritzmann et al. 2012) and neurons in protocerebral areas near the central body of the crayfish brain help control initiation of walking (Kagaya and Takahata 2011). Coordinating neurons that project through crustacean thoracic ganglia help coordinate the half-center oscillators for leg depression/elevation and promotion/remotion that underlie forward and backward walking (Cattaert and Le Ray 2001). These networks presumably translate unpatterned descending “commands” into patterns of coordinated leg movement, although the details are unknown. Nonetheless, the thoracic motor patterns bear a remarkable resemblance to analogous patterns in vertebrate spinal cord (Clarac and Pearlstein 2007; Duysens et al. 2000).

### 9.5.5 Sensory Feedback in the Maintenance of Posture

Little is known of how descending commands for a given static posture are distributed among the elements of the thoracic nervous system. Nonetheless, it is clear that static postures are maintained through negative feedback resistance reflexes in which nearly

all the proprioceptors and exteroceptors of the leg participate. This process is particularly well understood in crayfish. Two TC joint sense organs mediate resistance reflexes that maintain leg anterior/posterior position. Leg movement forward excites afferents from the TC chordotonal organ (TCCO), which in turn excite leg remotor MNs and inhibit leg promotor MNs (Skorupski and Sillar 1986). Backward leg movement excites afferents of the TC muscle receptor organ (TCMRO), which then excite promotor MNs and inhibit remotor MNs.

At the CB joint, an elastic strand receptor, the coxobasal chordotonal organ (CBCO), mediates resistance reflexes that maintain leg position against elevation and depression. Twenty release-sensitive CBCO afferents respond to leg elevation by exciting depressor MNs and inhibiting levator MNs. Leg depression excites 20 stretch-sensitive CBCO afferents with opposite effects (El Manira et al. 1991a). As in insects and vertebrates, the excitatory resistance reflexes are monosynaptic and the inhibitory reflexes are di- or polysynaptic. For both the stretch- and release-sensitive CBCO afferents, some respond to CBCO stretch or length, some to rate of stretch, and some to both. Like the vertebrate Ia resistance reflex, the CBCO resistance reflex acts as a PID controller to help maintain posture. Cuticular stress detectors (CSDs), located near the CBCO, respond to cuticle stress evoked by depression of the leg against the substrate and excite the levator MNs in a negative feedback reflex (Leibrock et al. 1996).

Insects have similar posture-maintaining resistance reflexes. Campaniform sensilla (CS) are functionally similar to crustacean CSD receptors. In cockroach tibia, proximal CS excite extensor MNs and inhibit flexor MNs and distal CS have reverse effects (Zill et al. 1981). In stick insect, an array of CS responds to the amplitude and rate of loading or muscle forces in directions out of the plane of leg movement. They excite leg retractor and protractor MNs in response to cuticular stress applied to the leg in a negative feedback reflex to reduce the stress (Schmitz 1993; Zill et al. 2012).

Many resistance reflexes span more than one joint, so that the leg movements are directed in more than a single plane. For example, stretch-sensitive CBCO afferents excited by leg depression excite levator MNs (CB joint) to resist the depression. They also excite leg remotor MNs (TC joint) that move the leg backward, and leg extensor (mero-carpopodite joint) and leg bender (CP joint) MNs to extend and pronate the leg. Raising the leg excites the antagonist MNs at all these joints (Clarac et al. 1978). Wider divergence of sensory effects is also seen. Polysynaptic reflex responses in locusts are produced by afferents that excite non-spiking interneurons with wide effects in the thoracic ganglion (Burrows et al. 1988) and, through projecting intersegmental interneurons, on adjacent legs as well (Laurent and Burrows 1989). Reflexes evoked by single proprioceptors or exteroceptors are thus part of a complex, but poorly understood, postural control system that works to stabilize posture through many parallel negative feedback pathways. These pathways diverge from each sense organ and converge from several sense organs onto sets of MNs that stabilize movements around multiple joints.

### 9.5.6 Sensory Feedback in Movement and Walking

The limb simulation above (Fig. 9.4) shows that the negative feedback control typical of resistance reflexes can also be used to control dynamic movement patterns by changes in the efferent control of the stretch receptor. Among arthropod leg receptors, only muscle receptor organs (MROs) provide for efferent control, with motor neurons projecting



to the receptor muscle (RM) of the MRO either alone or to the homonymous working muscle as well (Head and Bush 1991). As in the spindle model (Fig. 9.4), co-activation of the RM and working muscle can excite afferent feedback to efferents of the working muscle to provide additional muscle activation at the beginning of each contraction phase, with afferent discharge decreasing as the RM shortens with limb movement.

Nervous systems exist in "quiescent" states where rhythmic motor patterns are inactive and resistance reflex responses are the rule, and "active" states characterized by at least some rhythmic motor activity and active resistance and assistance reflex responses (Chung et al. 2015; Le Ray and Cattaert 1997). Rhythmically activated resistance reflexes can produce rhythmic motor patterns in quiescent nervous systems, but these are readily seen to be artifactual. For example, when recording from an isolated crayfish nervous system with an intact CBCO, imposed sinusoidal CBCO stretch and release induces alternating levator/depressor and remotor/promotor activity suggestive of backward walking (El Manira et al. 1991b). However, the stretches and releases that would occur during actual backward walking are opposite to the imposed CBCO movements. Thus, if these resistance reflexes occurred in a walking animal, they would oppose the movement. This does not happen in active preparations or during walking, indicating that such unwanted resistance reflexes are prevented from occurring when the nervous system is in the active state.

Unwanted reflexes are prevented in both arthropods and vertebrates by pre-synaptic inhibition of the synapses between the afferents and the motor neurons that mediate the reflex (Büschges and Wolf 1999; Cattaert et al. 1992). Pre-synaptic inhibition targets the afferent-to-interneuron connection that mediates the reflex, and often spares the outputs of the same afferents to other targets and the responses of the motor neurons to other inputs. Pre-synaptic inhibition often takes the form of the PAD explained earlier (Eccles et al. 1962; Kennedy et al. 1974). In locust, PAD occurs in central terminals of proprioceptor (FCO) afferents produced by di-synaptic inputs arising from other afferents (Burrows and Laurent 1993). In crayfish, PAD occurs in the central terminals of CBCO afferents and of dactyl sensory afferents (Cattaert et al. 1992; Marchand et al. 1997), where it acts by shunting or inactivating spikes at or before they reach the pre-synaptic terminal (Cattaert and El Manira 1999; Edwards 1990). Strong pre-synaptic inputs can also sufficiently depolarize the pre-synaptic terminal to evoke spikes that travel antidromically to the distal spike generating mechanism of the afferent. Antidromic spikes can inhibit the spike generating mechanism for hundreds of milliseconds, thereby preventing afferent participation in all reflex responses (Cattaert et al. 1999; Gossard et al. 1999).

Not all resistance reflexes are unwanted during walking. During the early part of stance, when the leg is firmly planted and bearing a load, a resistance reflex to upward perturbation of the leg would be helpful. Depolarization of crayfish leg depressor MNs, which occurs in stance, increases their resistance reflex responses to CBCO afferents, and so may help resist upward leg perturbations during early stance (Le Bon-Jego et al. 2006).

*Reflex Reversal* As mentioned above, in active preparations, imposed sinusoidal CBCO movement entrains a rhythm with reversed reflex responses: CBCO stretch, which occurs during leg depression, evokes a depressor MN burst, and CBCO release, which occurs during leg elevation, evokes a levator MN burst (Le Ray and Cattaert 1997).



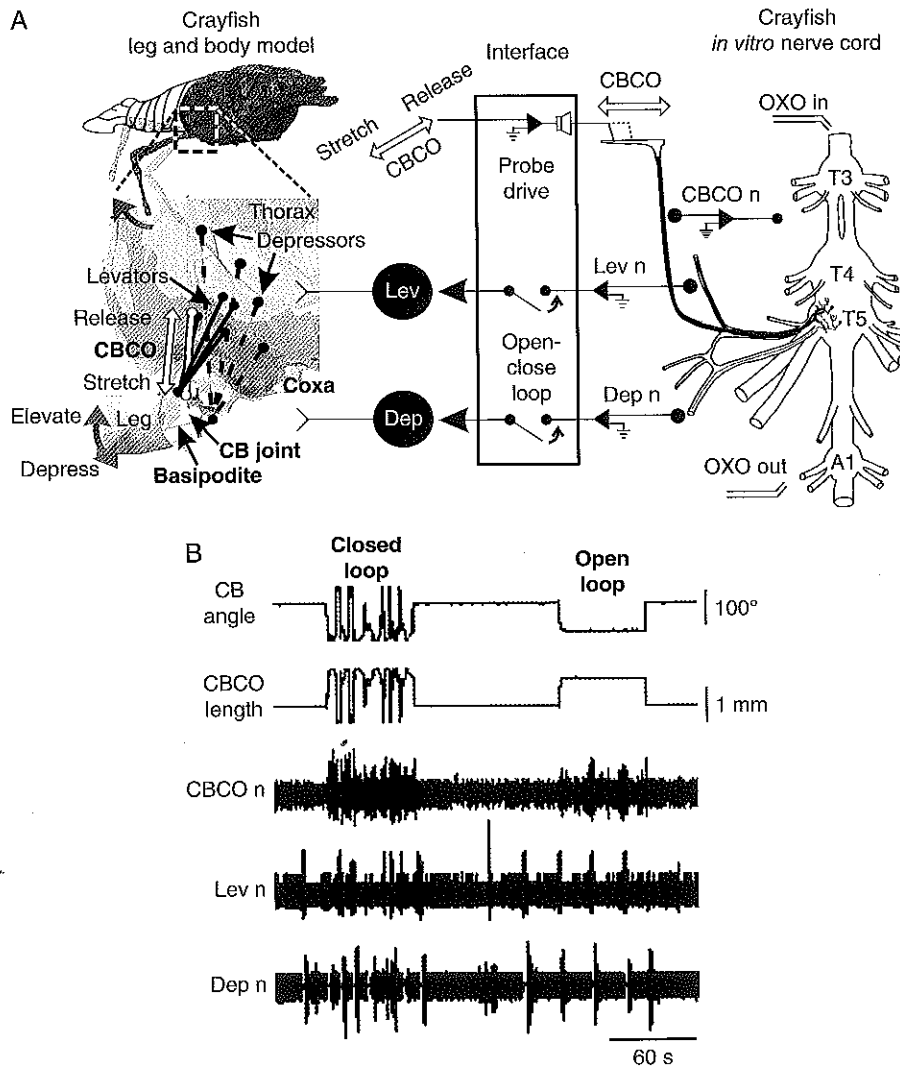
CSDs also reverse their reflexes in active preparations and entrain levator and depressor MN activity (Leibroek et al. 1996). Reflex reversal also occurs at other joints in the same leg upon transition from a quiescent to an active state. For example, protraction and retraction of TCMRO/TCCO stretch receptors evoke resistance reflexes in the quiescent state and assistance reflexes in the active state (DiCaprio and Clarac 1981; Sillar et al. 1986; Skorupski et al. 1992).

Similar reflex reversals occur in insects. In stick insect, the femoral chordotonal organ (fCO) responds to flexion and extension of the flexor–tibia joint. fCO-mediated resistance reflexes become assistance reflexes when nervous system state shifts from quiescent to active (Bässler 1976; Büschges 2012; Zill et al. 2012). In cockroach, leg remotion during walking produces strains in the leg cuticle that excite the trochanteral campaniform sensilla; they then excite leg depressor MNs that produce leg remotion. This positive feedback, assistance reflex response is enhanced when an added load increases resistance to leg remotion during walking (Pearson 1972). Reflex reversal depends on context as well as nervous system state (Hellekes et al. 2012). Reflex reversal in stick insects is enhanced during forward, but not backward, walking, and by stepping of the rostral ipsilateral leg, but not contralateral legs. During curve walking, fCO promotes leg flexion of the inside middle leg but not the outside leg.

*Mechanisms of Reflex Reversal* Network pathways for assistance reflexes are less well understood than resistance reflex pathways. Two mechanisms for assistance reflexes have been proposed: persistent changes in the relative strength of parallel excitatory and inhibitory pathways from sensory neurons to motor neurons, and a switch in the reflex pathway to the opposite side of the half-center CPG (Büschges et al. 2011; Cattaert and Le Ray 2001). Details of these mechanisms have been obtained for the leg depressor assistance reflex in crayfish (Clarac and Cattaert 1996; Le Ray and Cattaert 1997). In quiescent preparations, 8 of the 12 leg depressor MNs were excited (resistance reflex response) by CBCO release (leg lift) and one depressor MN was excited (assistance reflex response) by CBCO stretch (leg depression). In active preparations, CBCO release excited few or no depressor MNs, whereas CBCO stretch excited strong assistance reflex responses from several depressor MNs.

These assistance responses were mediated by an assistance reflex interneuron (ARIN) that forms a di-synaptic pathway between stretch-sensitive CBCO afferents and depressor MNs (Le Ray and Cattaert 1997). ARIN was inhibited in the quiescent state, but was responsive in the active state, in which post-synaptic responses were amplified by a voltage-sensitive inward current. Phase-sensitive modulation of this network may come from CPG inputs that depolarize ARIN at the swing-to-stance transition (Cattaert and Le Ray 2001). Similar inputs may gate pre-synaptic inhibition of primary afferents to inhibit resistance reflexes when they would inappropriately oppose CPG driven leg movements.

The role of assistance reflexes during walking became apparent in experiments in which the sensory feedback loop was opened or closed at will. This was possible with a “hybrid preparation” in which an *in vitro* crayfish thoracic nervous system and CBCO were attached to a computational neuromechanical model of the crayfish body and 5<sup>th</sup> leg (Fig. 9.6A) (Chung et al. 2015). Recorded activity of levator and depressor motor nerves from the 5<sup>th</sup> thoracic ganglion excited model levator and depressor leg muscles, and their contractions drove the model leg up and down (Fig. 9.6B). The live CBCO was



**Figure 9.6** Closed loop responses in a hybrid biological/neuromechanical preparation of crayfish leg elevation/depression. (A) Experimental set-up. Recorded activity from the depressor (Dep n) and levator (Lev n) nerves (right) drives corresponding muscles of a neuromechanical model of the leg and body (left). Leg up and down movements release and stretch a model CBCO. Model CBCO movements cause a speaker-driven probe to move the real CBCO identically. CBCO afferent projections to the nervous system complete the feedback loop. Switches in the interface between the preparation and model (middle) permit opening the feedback loop. Oxotremorine, a muscarinic agonist, was applied to the preparation to make it active. (B) Activity of model leg (CB) angle (top), CBCO length, and CBCO n, Lev n, and Dep n activity in trials with feedback loop closed, open, and when simulation was not running (rest of time). Adapted from Chung et al. (2015).

released and stretched according to the model leg movements, and the resulting CBCO afferent activity projected back to the thoracic ganglion to complete the feedback loop.

When the nerve cord was in a quiescent state, brief imposed lifts of the model leg evoked chained resistance reflexes, exciting depressor MNs during leg lift and levator MNs during leg fall (Chung et al. 2015). Exposure to oxotremorine, a muscarinic agonist, caused the cord to gradually enter the active state. Leg lifts made early in this state evoked levator MN assistance reflexes, a levator MN burst immediately followed by a depressor MN burst. Shortly thereafter, these levator/depressor burst pairs occurred spontaneously at low frequency ( $\sim 1/25$  s) when the feedback loop was open and became nearly three times faster when the feedback loop was intact. During these closed loop periods, spontaneous levator/depressor burst pairs produced rhythmic up and down leg movements every 10 s that ended only when the feedback loop was opened at the end of the model simulation.

The assistance reflexes evoked by upward leg movement in closed loop conditions appear to be responsible for the increased frequency of motor burst pairs and up/down leg movements. The levator/depressor burst pairs that occurred in open loop were largely unchanged in closed loop, but the interval between the depressor burst of one burst pair and the levator burst of the next shortened significantly. Levator activity increased gradually following each depressor burst, and in closed loop the levator MNs evoked small upward leg movements that were then amplified by the assistance reflex. As occurred with imposed leg lifts, the assisted upward movements triggered the levator/depressor burst pair well before it would have occurred without the intact feedback loop. The early triggering of the burst pair in each cycle reset the levator/depressor CPG each cycle and accounted for the increased frequency of the levator/depressor rhythm.

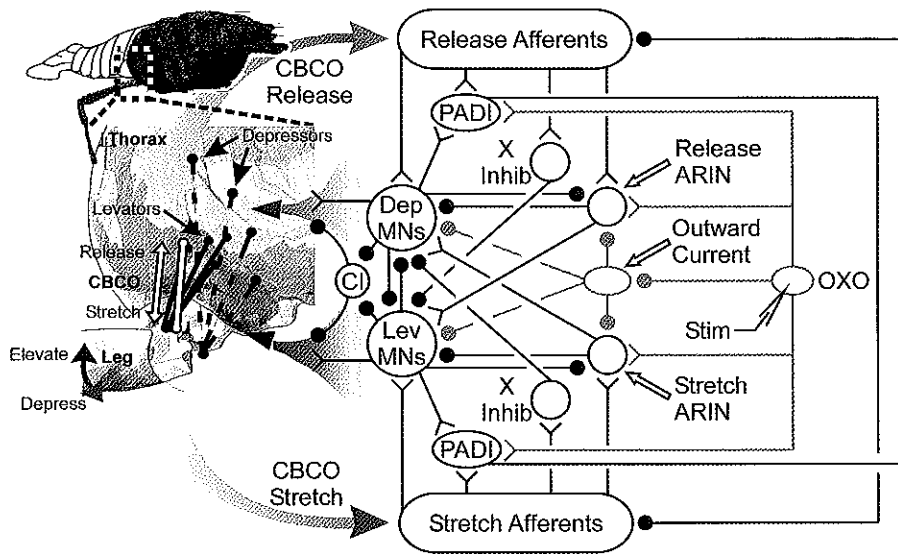
These conclusions were supported by simulations using a model of the hybrid preparation (Fig. 9.7A) (Bacque-Cazenave et al. 2015). In this model, a model neural network was developed from descriptions of the networks that control levator and depressor MNs during quiescent and active states (Cattaert and Le Ray 2001). The model network was substituted for the *in vitro* nervous system, linked to the same leg and body model used in the hybrid experiments, and used to simulate the leg lift experiments in the quiescent and active states and the open and closed loop configurations in the active state. The model reproduced all of the results of the hybrid experiments (Chung et al. 2015), including increased MN bursting frequency in closed loop conditions (Fig. 9.7B) (Bacque-Cazenave et al. 2015). This showed that the circuit configurations of the quiescent and active states (Cattaert and Le Ray 2001) could account for the reflex reversal and the effects of opening and closing the feedback loop on levator/depressor bursting behavior. Moreover, it showed that the ARINs and their assistance reflexes played an essential role in speeding the bursting rhythm in the closed loop, active state preparation.

These data suggest that the TCMRO/TCCO feedback loops that govern TC joint forward/backward movements likely have similar accelerating effects on motor rhythm frequency. Open loop experiments have shown that assistance reflexes occur on both stretch and release when the TCMRO and TCCO are stimulated together as they are in the intact leg, and that these reflexes can entrain the promotor/remotor CPG (Sillar et al. 1986; Skorupski et al. 1992). Moreover, the subpopulation of promotor and remotor MNs excited in assistance reflexes has lower thresholds for excitation

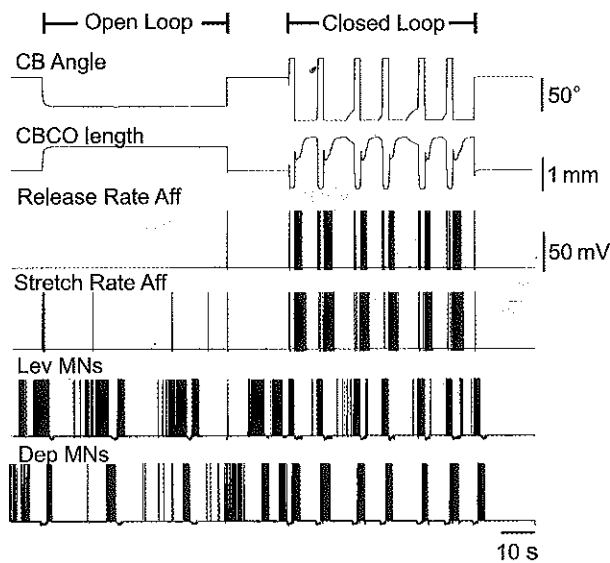


## A Crayfish leg and body model

## Neural circuit model



## B



**Figure 9.7** (A) The neuromechanical model of the hybrid preparation. A neural network containing integrate and fire model neurons replaces the *in vitro* preparation. (B) Model activity under open loop and closed loop conditions when the network was activated by stimulating the OXO neuron to simulate oxtremorine effects. Excitatory synapses: forks; inhibitory synapses: filled circles. Adapted from Bacque-Cazenave et al. (2015).



by the promotor/remotor CPG. It appears likely that, when leg elevation assistance reflexes mediated by the CBCO trigger the levator/depressor burst pair, leg promotion assistance reflexes mediated by the TCMRO/TCCO will trigger a near-simultaneous promotor/remotor burst pair.

*Feedback in Locomotor Phase Transitions* Stance/swing and swing/stance transitions are also promoted in decapod crustaceans by feedback pathways from other leg sensory organs. Stimulation of funnel canal organs (FCO) in the dactyl of the crab leg facilitates stance/swing transitions during walking by exciting levator and promotor MNs and inhibiting depressor and remotor MNs (Libersat et al. 1987a,b). In response to FCO stimulation in crayfish, levator excitation was accompanied by depressor inhibition in the stimulated leg to facilitate its swing phase and by depressor excitation in adjacent legs to promote their stance phase (Clarac et al. 1991). In rock lobster, FCO nerve stimulation cut stance short and triggered swing, whereas stimulation at the end of swing delayed the onset of the next stance (Muller and Clarac 1990).

CS play similar roles in insects by responding to the changes in force in the leg cuticle that accompany swing-stance transitions. In cockroach, distal CS receptors in the middle leg were strongly excited towards the end of stance as force on the leg decreased when the hind leg entered stance and took up the ipsilateral load (Zill et al. 2009). A similar pattern of CS activation occurs in locust legs, in which the decline in longitudinal tensile forces on the dorsal tibia prior to swing excites CS receptors (Newland and Emptage 1996). These help excite flexor motorneurons and inhibit extensor motorneurons, promoting the stance/swing transition. In the stick insect, CS input enhances retractor motor neuron activity during forward walking (Büschges 2012). The same CS input inhibits retractor motor neuron activity during backward walking, providing an example of context-dependent reflex reversal.

Insect joint stretch receptors also facilitate stance/swing transitions. The position response of the stick insect femoral chordotonal organ (fCO<sup>1</sup>) promotes stance/swing transition (Bässler 1993). Synergy between CS and fCO responses further promotes these transitions. Femoral CS stimulation alone inhibits leg extensor motorneurons at the end of stance more reliably but more slowly than fCO stimulation alone. Simultaneous stimulation of both receptor organs inhibits extensors with the reliability of CS stimulation and the speed of fCO stimulation (Akay and Büschges 2006). Swing/stance transitions similarly depend on feedback, primarily ground contact (Duysens et al. 2000). Motor neuron discharge during stance also depends on stance velocity, which varies throughout stance phase (Gabriel and Büschges 2007).

## 9.6 Organization and Function in Vertebrates

### 9.6.1 Sensory Feedback in the Maintenance of Posture

As in arthropods, postural control in vertebrates involves maintaining a specific body configuration, a set of joint angles, that keeps the body above the feet during standing, locomotion, and other movements, and resists sudden perturbations of posture. Proprioception, along with tactile, visual, and vestibular information, are involved in postural control to varying degrees depending on the number of legs on the ground, animal body

design, postural task, and perturbation characteristics. Quiet standing in quadrupeds is statically stable, meaning that the vertical projection of body center of mass is well within the area of support and small displacements of this projection therefore do not threaten body balance (Gray 1968; Horak and Macpherson 2011). In bipeds (birds, kangaroos, humans), quiet standing, and especially locomotion, are inherently mechanically unstable; even when the vertical projection of the center of mass is within the support area, without appropriate postural responses, small body sways accelerate the center of mass toward the border of support and lead to loss of balance (Hof et al. 2005; Winter 1995). Neural control mechanisms in human standing and postural reactions to perturbation are often studied by modeling the body as a single or double inverted pendulum with rotational axes at the ankle or ankle and hip joints. Body equilibrium in these models is controlled by joint moments generated by a feedback PID controller (Fig. 9.1) (Li et al. 2012; Masani et al. 2006; Peterka 2002).

Postural control involves integration of multiple sources of sensory feedback with feed forward motor commands at multiple levels in the central nervous system (Horak and Macpherson 2011; Nashner et al. 1989). The specific contribution each input makes to spinal motorneuron pools is difficult to establish experimentally *in vivo*. Therefore, various experimental paradigms, reduced animal preparations, and neuromechanical modeling are necessary to fully understand the mechanisms of sensory control of posture.

**Muscle Length Feedback** Unexpected shifts of the vertical projection of body center of mass toward the border of the support area lead to re-configuration of body limbs and corresponding changes in the length of muscles affected by the limb joint motion, i.e., some muscles stretch while their anatomical antagonists shorten. Greater lengthening and shortening occur in muscles with longer moment arms (An et al. 1984; Landsmeer 1961). Muscles with greater stretch have a greater mechanical advantage in generating movements opposing joint angle and limb configuration changes. Muscle stretch produces force responses due to intrinsic muscle properties and stretch-evoked muscle reflexes.

Intrinsic musculoskeletal properties contribute substantially to postural control. The position restoring response to externally imposed limb displacements, the apparent stiffness of a multi-joint limb, depends in part on limb configuration. This property derives directly from geometric analysis of the transformation between small displacements of the limb endpoint and the corresponding changes in limb joint angles (Hogan 1985; Mussa-Ivaldi et al. 1985). Human arm and cat hindlimb forces generated in response to sudden small horizontal shifts of limb endpoint are restrained to directions passing close to the limb proximal joint (Macpherson 1988a; Mussa-Ivaldi et al. 1985). This response appears to be a consequence of limb musculoskeletal anatomy irrespective of muscle activation (Bunderson et al. 2010).

Intrinsic muscle force-length and force-velocity properties (muscle short-range stiffness) instantaneously resist muscle stretch before any stretch reflexes are evoked (Joyce et al. 1969; Malamud et al. 1996; Rack and Westbury 1969, 1974). Short-range stiffness is explained by elastic deformation of engaged cross-bridges and thus operates only over a relatively short muscle fiber elongation range, beyond which the bridges disengage and the rate of muscle force development decreases or changes sign (Flitney and Hirst 1978). Because short-range stiffness depends on the number of engaged cross-bridges,

its magnitude increases with muscle activation. Stretch reflexes, in particular the fastest monosynaptic stretch reflex, increase the length range over which muscle intrinsically resists imposed stretch (Huyghues-Despointes et al. 2003; Nichols and Houk 1976). Short-range stiffness is the first line of defense against postural perturbations, operating in the time period before muscle length feedback reaches the central nervous system and engages spinal stretch reflexes.

Stretch reflexes play the major role in generating postural responses to modest perturbations, ones not causing dramatic body displacements (Fig. 9.4). Muscle responses to small horizontal displacement of the support surface are directionally tuned (Henry et al. 1998; Macpherson 1988b)—muscle response is greater in directions in which a muscle is more stretched by the perturbation and provides more effective resistance to limb configuration change (Bunderson et al. 2010; Honeycutt and Nichols 2014). This directional tuning of muscle postural responses is at least partially mediated by muscle length sensitive afferents: activity of group Ia and II spindle afferents from medial gastrocnemius and biceps femoris muscles of anesthetized or decerebrate cats is tuned in the directions of postural responses of these muscles and opposite to the directions of support surface displacement (Honeycutt et al. 2012). This directional tuning arises from the directional dependence of limb muscle moment arms, which controls the amount the muscle is stretched by perturbation. This dependence results in perturbations activating muscles with the largest mechanical advantage for producing moments that correct the perturbation.

The magnitude of muscle stretch and spindle afferent responses to postural perturbations depends on the size and rate of the perturbations (Honeycutt et al. 2012). In cats (Eng and Hoffer 1997) and humans (Day et al. 2013; Loram et al. 2009), during quiet standing and relatively small perturbations of the ankle joint, muscle-tendon unit length changes in ankle extensors do not correlate well with muscle responses. This poor correlation is due to the long and compliant muscle tendon, which absorbs substantial length changes in the muscle-tendon unit complex. During standing, length changes in muscle fascicles are more closely related to muscle activity changes (Day et al. 2013; Eng and Hoffer 1997), which is expected given that the muscle spindles are embedded in parallel with muscle fascicles.

Other sensory signals are also involved in muscle directionally tuned postural responses. Selective destruction of large-diameter sensory axons (primarily Ia and Ib fibers) in cat hindlimb delays muscle responses to horizontal support displacements two to three times but does not affect directional tuning of muscle activity (Stapley et al. 2002). Removal of hindlimb cutaneous feedback in decerebrate cats reduces the magnitude, but not the directional tuning, of muscle responses to support perturbations (Honeycutt and Nichols 2010).

*Load-Tactile Feedback* Postural perturbations change the pressure on the skin of the limb end-segment in contact with the support and loading on affected muscles. Skin pressure and deformation are detected by skin mechanoreceptors (Abraira and Ginty 2013) whereas changes in muscle forces are registered by Golgi tendon organs (Jami 1992). Even a very light fingertip touch of a stationary object profoundly reduces postural sway in standing humans (Jeka and Lackner 1994), possibly by providing information about the direction of body sway. The ability of skin mechanoreceptors in contact with the support surface to sense the direction of surface shift has been implicated in shaping



muscle and joint moment directional responses to postural perturbations (Jacobs and Macpherson 1996; Meyer et al. 2004). Detection of perturbing horizontal forces by tactile sensitive afferents in the foot or paw provides information about the direction of the center of mass acceleration, as the ground reaction forces reflect the resultant external forces, and thus acceleration, at the body center of mass. This may provide an explanation for the fact that the body center of mass acceleration and other center of mass kinematic variables are predictive of muscle long-latency postural responses in humans (Safavynia and Ting 2013). Acute denervation of the paw pad in decerebrate cats, alternatively, does not affect the directional tuning and latency of muscle postural responses to horizontal shifts of the support surface and reduces only the background activity and magnitude of muscle responses. In these experiments, the animal's head was fixed, and hence visual and vestibular inputs were unchanged by the support shifts.

Human postural control possibly differs from that of cats because a standing human, accurately represented as an inverted pendulum with the rotational axis at the ankle joint, is inherently unstable (Winter 1995). Ankle joint angle, fascicle length (and thus muscle spindle length) of ankle extensors, and center of mass position changes, do not correlate with ankle extensor activity. Rather, the human postural control system responds to changes in center of mass velocity with a delay of several hundred milliseconds (Loram et al. 2005), thus exhibiting integral feedback control (Fig. 9.1). Center of mass velocity during postural sway could be potentially derived from horizontal forces sensed by cutaneous afferents on the plantar surface of the foot, as discussed above.

### 9.6.2 Sensory Feedback and its Integration with Motor Commands in Movement

During movements, muscle length and force-dependent reflexes are modulated, and sensory feedback pathways reorganized, to meet a wide range of behavioral requirements. This reflex modulation is required, as in invertebrates, because posture stabilizing reflexes would be detrimental for movement production. For example, during quiet standing in the cat, extensor muscles are active to support the body against gravity and antagonistic flexor muscles are relaxed (Torres-Oviedo et al. 2006). If standing posture is perturbed by a horizontal shift of the support, muscles stretched by the perturbation, irrespective of their extensor or flexor function, respond with strong corrective activity (Torres-Oviedo et al. 2006). This response is automatic and mediated in part by length-dependent sensory pathways in the spinal cord (Macpherson and Fung 1999). If these reflexes were operational when the cat made a step by flexing and then extending the limb, extensor muscles being stretched during flexion, and flexor muscles stretched during extension, would activate stretch reflexes opposing the intended movement.

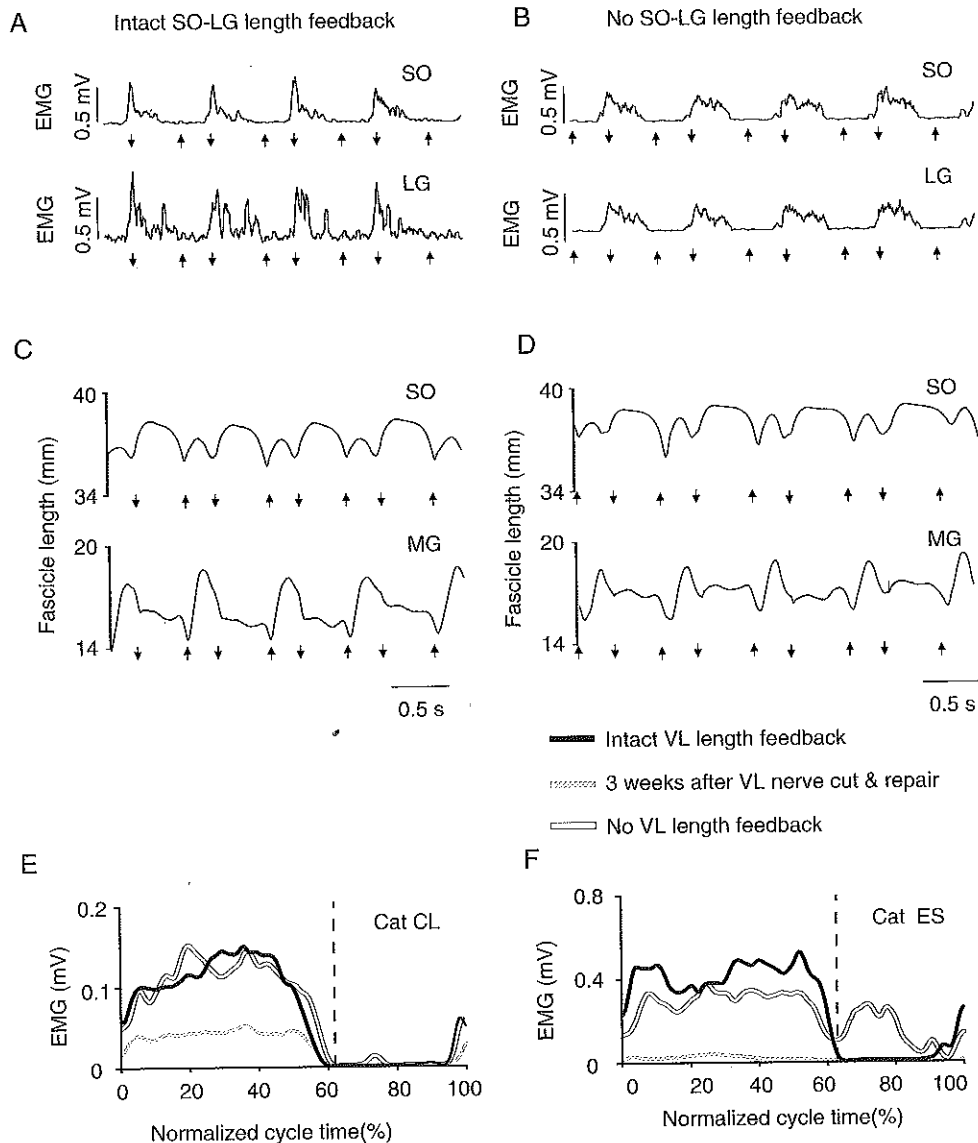
The nervous system resolves this problem (von Holst and Mittelstadt 1950) by changing spinal reflex properties and reconfiguring interneuronal pathways. Task- and phase-dependent reorganizations of reflexes during movements occur at the levels of synaptic transmission of afferent signals, spinal locomotor pattern generating networks, and supraspinal centers. One important mechanism disabling stretch reflex in antagonistic muscles during movements is reciprocal inhibition via Ia inhibitory interneurons—agonist motoneuron activity coincides with activity of Ia inhibitory interneurons that inhibit antagonist motoneurons (Feldman and Orlovsky 1975) (X-Inhib interneurons in Fig. 9.4A).

*Regulation of Spinal Stretch Reflexes* The gain of stretch reflex from agonists is substantially reduced during movements compared to the rest condition or postural tasks. For example, the Hoffman (H-) reflex, which is evoked by electrical stimulation of Ia afferents instead of by spindle stretch (Misiaszek 2003), is lower during human running than walking, and lower during walking than standing (Stein and Capaday 1988). In decerebrate cats, the gain of the stretch reflex is similarly reduced during walking compared to rest (Bennett et al. 1996). Compared to rest, the amplitude of motorneuron monosynaptic excitatory post-synaptic potentials (EPSPs) evoked by group I afferent electrical stimulation in the decerebrate cat is significantly depressed during brainstem-evoked fictive locomotion (Gosgnach et al. 2000). This depression arises from tonic suppression by spinal GABAergic interneurons of neurotransmitter release at group Ia afferent synapses onto motorneurons and interneurons (Fig. 9.4). Genetic elimination of spinal GABAergic interneurons in mice, and hence removal of pre-synaptic inhibition of length-dependent afferent feedback, results in severe forearm oscillations during voluntary reaching movements but does not impair locomotion (Fink et al. 2014). These results, and simulations of limb movements with high gain length feedback (Fig. 6 in Fink et al. 2014), suggest that reduced gains of length feedback during voluntary reaching ensures smooth performance.

Other mechanisms of reflex gain regulation also occur during movements. One of these is fusimotor control of muscle length feedback (Hulliger et al. 1989; Taylor et al. 2006), which adjusts static and dynamic responses of length sensitive muscle spindle afferents to specific motor task requirements (Fig. 9.4) (Hunt 1990; Matthews 1981). Tendon stretches during walking in decerebrate cats (Stein et al. 2000) and computer simulations (Yakovenko et al. 2004) show that length dependent feedback from ankle extensor muscles contribute about 30% to their locomotor activity. Similar estimates have been obtained in humans by imposing quick stretches in ankle extensor muscles during walking (Mazzaro et al. 2005). On the other hand, permanent removal of stretch reflexes from selected ankle (Gregor et al. 2014; Pantall et al. 2016) and knee extensors (Mehta et al. 2014) by self-reinnervation of these muscles (Alvarez et al. 2010; Bullinger et al. 2011; Cope et al. 1994; Cope and Clark 1993; Lyle et al. 2016) does not decrease muscle activity during level, upslope, and downslope walking (Fig. 9.8) and causes (minor) kinematic deficits in only downslope walking (Abelew et al. 2000; Maas et al. 2007). Thus, effects of length dependent feedback on activity of ankle and knee extensors during locomotion are unclear and require further study.

In another rhythmic task, cat paw shake response, removing knee extensor length-dependent feedback changes vastus medialis activity (Mehta et al. 2014), but removing ankle extensor length-dependent feedback does not alter ankle extensor activity (Mehta and Prilutsky 2014). This dependence of vastii activity and independence of ankle extensor activity on length dependent feedback during paw shake is consistent with data obtained by constraining knee motion during paw shake and hindlimb deafferentation in spinal cats (Smith and Zernicke 1987). Thus, in some rhythmic tasks, length dependent feedback from knee extensors is critical for correct movement execution.

*Stance-Swing and Swing-Stance Transitions* Length-sensitive hip muscle spindle group Ia and II afferents help regulate locomotor phase transitions. Manipulating hip joint angle



**Figure 9.8** Locomotor EMG activity and fascicle length in ankle and knee extensor muscles with length feedback removed by muscle self-reinnervation. Downward vertical arrows indicate stance onset, upward vertical arrows swing onset. (A, C) Low-pass filtered EMG activity and fascicle length of intact soleus (SO), lateral gastrocnemius (LG), and medial gastrocnemius (MG) muscles of a cat during level walking. (B, D) Low-pass filtered EMG activity and fascicle length of self-reinnervated SO and LG and intact MG muscles in the same animal as in A and C. Adapted from Pantall et al. (2016). (E, F) Low-pass filtered EMG activity of vastus lateralis (VL, mean) of two cats during 27° upslope walking in intact condition (black filled lines), 3 weeks after nerve cut and repair (gray filled lines), and after muscle self-reinnervation (12–14 weeks after nerve repair; unfilled gray lines).

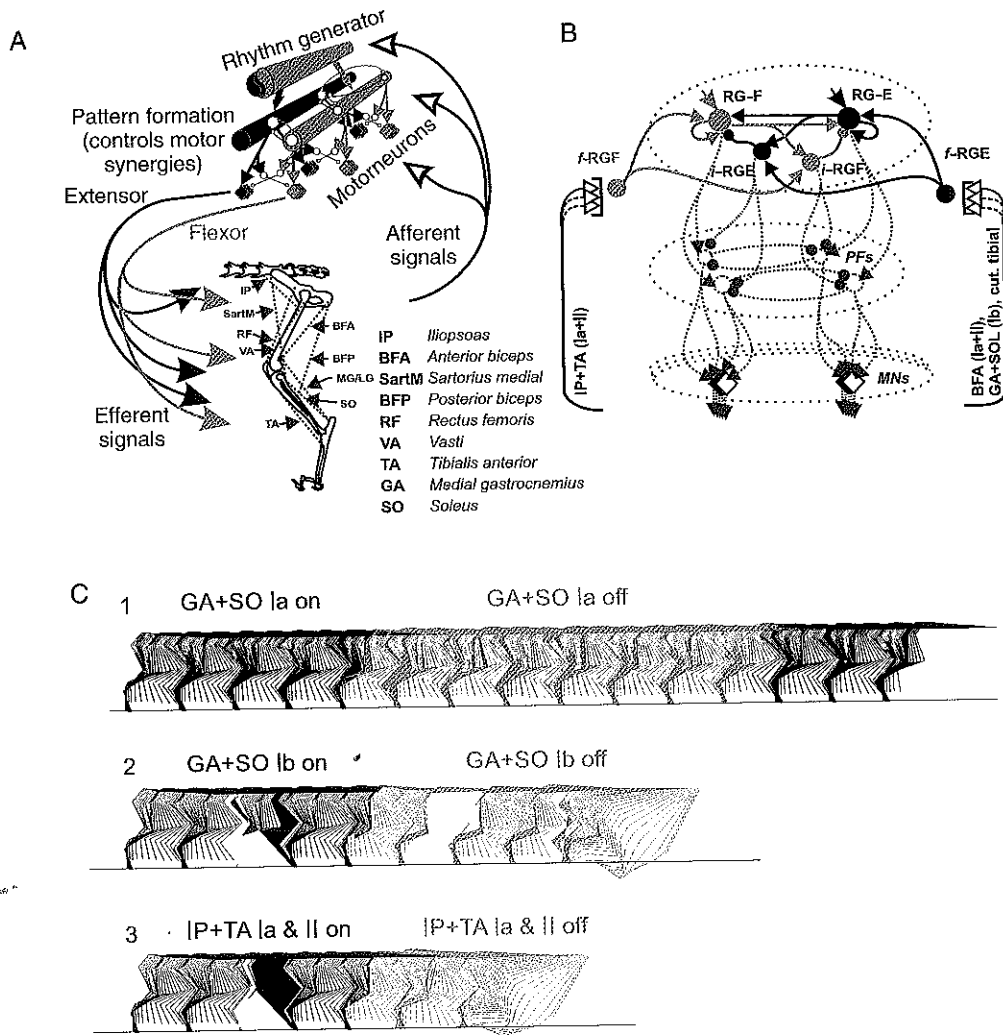


entrains locomotor rhythms in spinal or decerebrate cat (Andersson and Grillner 1983; Hiebert et al. 1996; Kriellaars et al. 1994). Resisting or assisting hip flexion during walking increases and decreases flexor activity, respectively, in decerebrate or intact cats (Lam and Pearson 2001), whereas vibrating or stretching hip flexors or stimulating their nerves at intensities that activate group I and II afferents during the extensor (stance) phase of real or fictive locomotion shortens ongoing extensor activity and promotes the onset of flexor activity (Hiebert et al. 1996; Lam and Pearson 2002; Perreault et al. 1995). Thus, length-sensitive group I and II spindle afferents from hip flexor muscles regulate extensor (stance)-flexor (swing) phase transitions by providing excitatory input to the flexor CPG half-center (Fig. 9.9A, B).

The role of length feedback from hip and ankle flexors in extensor–flexor phase transitions in cat locomotion has also been investigated using a neuromechanical model of spinal locomotion (Markin et al. 2016). In the model the central pattern generator for each hindlimb is controlled by hindlimb afferent signals from group I and II muscle and paw pad cutaneous afferents (Fig. 9.9A, B) and reproduces the muscle activity and mechanics of the walking cat. Removing length feedback from hip and ankle flexors causes the model to collapse after three strides (Fig. 9.9C3). This shows that length feedback from flexors regulating CPG stance–swing transitions is required for proper control of stance phase duration.

There is also a strong correlation between hip flexion angle (McVea et al. 2005) or muscle-tendon unit length of hip extensors (Gregor et al. 2006) and the onset of extensor activity during level, downslope, and upslope cat walking, indicating the importance of length sensitive afferents from hip extensors in regulating flexor (swing)–extensor (stance) phase transitions during locomotion via excitatory input to the CPG half-extensor center (Fig. 9.9B). Hip muscle length-dependent feedback is necessary, but not sufficient, for locomotor phase resetting. This is illustrated by comparing hip joint angles during walking on a split belt treadmill with the two belts operating at different speeds. The slower moving leg has a shorter stride length and smaller joint range of motion than the hip of the faster leg (Malone and Bastian 2010). Stance–swing phase transitions can thus occur at different lengths of hip flexors and extensors.

*Cat Ankle Extensor Tension* The other sensory cue for stance–swing transition is load-dependent signals from group I ankle extensor afferents. Electrical stimulation of ankle extensor nerves at intensities activating group I spindle and Golgi tendon afferents during flexor activity in fictive or real locomotion resets locomotion to extensor activity, whereas the same stimulations during the extensor phase increase extensor activity and duration throughout the hindlimb (Gossard et al. 1994; Guertin et al. 1995). The locomotor rhythm resetting and changes in activity across hindlimb extensors suggest that the responses are mediated by the extensor half-center of the CPG (Fig. 9.9B). Thus, unloading of muscle force-sensitive group Ib Golgi tendon organ afferents and the reduction of input from length-sensitive group Ia spindle afferents due to muscle shortening at stance end diminish the excitatory input to the extensor CPG half-center and contribute to initiation of the extensor–flexor transition (Duysens and Pearson 1980; McCrea and Rybak 2008). Feedback signals from group I ankle extensor afferents may also provide inhibitory input to the flexor CPG half-center that modulates its activity and phase transitions (Pearson 2008).



**Figure 9.9** Neuromechanical simulation of spinal locomotion with selective removal of muscle proprioceptive feedback. (A) Model schematic. A 10 degree-of-freedom musculoskeletal system of two hindlimbs (only one shown) with 18 Hill-type muscles controlled by a two-level locomotor CPG consisting of a rhythm generator and a pattern formation network (Rybak et al. 2006a,b). CPG activity is regulated by sensory feedback from group I and group II muscle and paw pad cutaneous afferents. (B) Afferent projections onto the rhythm generator. f-RGF interneurons are excited by Ia and II spindle afferents from hip flexor iliopsoas (IP) and ankle flexor tibialis anterior (TA) muscles and these afferents excite the flexor half-center of the rhythm generator (RG-F). i-RGE interneurons are excited by Ia and II afferents of hip extensor biceps femoris anterior (BFA), Ib afferents of ankle extensor soleus (SO) and gastrocnemius (GA), and paw pad cutaneous afferents (cut. tibial) and these afferents excite the extensor half-center of the RG (RG-E). MNs are motor neurons. (C) Walking kinematics before and after removal of selected sensory feedback. Black stick figures are last 4 cycles of 40 s of walking with intact feedback before turning off specific feedback types; gray figures show effects of feedback removal. 1) Removal of length dependent Ia feedback from SO and GA. 2) Removal of force dependent Ib feedback from SO and GA. 3) Removal of length dependent Ia and II feedback from IP and TA. Adapted from Markin et al. (2016).

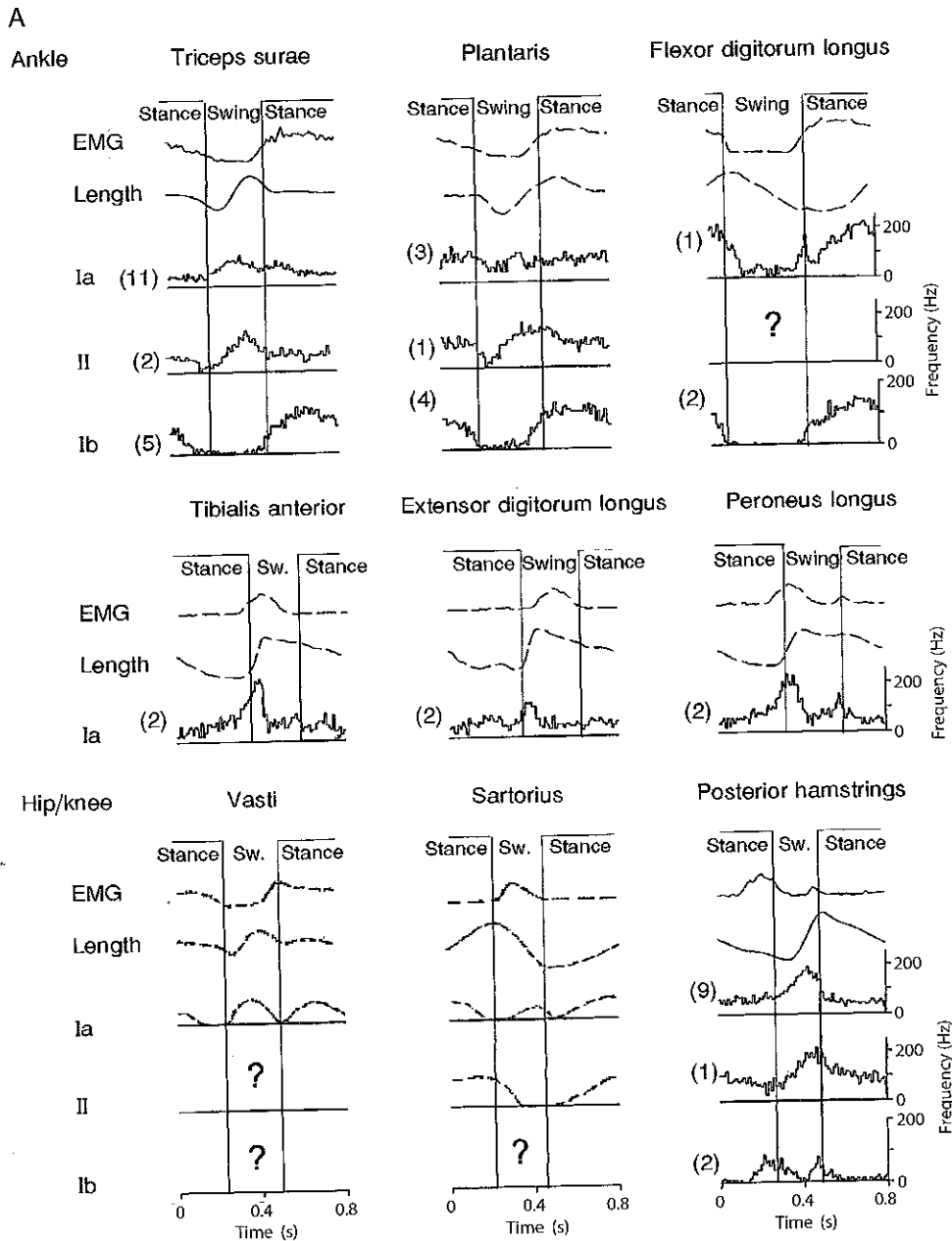
It is difficult to separate the contribution of length-dependent and force-dependent afferent feedback to activity in fictive or real locomotion because activation thresholds of group Ia and Ib afferents to muscle nerve electrical stimulations are similar and evoking the stretch reflex by stretching the muscle also increases muscle force due to muscle force-length-velocity properties (Joyce et al. 1969; Rack and Westbury 1969). Modeling can help identify the relative contributions of length and force feedback (e.g., Bacque-Cazenave et al. 2015; Ekeberg and Pearson 2005; Markin et al. 2010). In such neuromechanical modeling the CPGs of the neural control system and the motion-dependent afferent signals of the musculoskeletal system are implemented together (Fig. 9.9). Parameters of the two parts of the model are typically tuned separately to ensure that the neural model reproduces the activity in muscle nerves during fictive locomotion (i.e., without motion dependent feedback) (Rybak et al. 2006a,b), and the musculoskeletal model reproduces real locomotion using recorded muscle activity as input (Prilutsky et al. 2016). The neuromechanical model of cat hindlimb locomotion developed in Markin et al. (2016) reproduces muscle activity and mechanics of level walking and thus allows simulation of the effects of removal of length-dependent feedback from ankle extensors (Fig. 9.9C1) and hip and ankle flexors (Fig. 9.9C3).

These simulations suggest that length feedback from ankle extensors during walking is not critical because its removal does not cause visible changes in walking mechanics. This conclusion is supported by the small changes in soleus and gastrocnemius EMG locomotor activity induced by removal of their stretch-reflexes *in vivo* (Fig. 9.8A-D). Furthermore, during early stance in level walking, when the muscle-tendon length of medial gastrocnemius muscle is increasing (Gregor et al. 2006; Maas et al. 2007), the muscle's fascicles do not lengthen and hence the spindles embedded in parallel with the fascicles should not either (see also Griffiths 1991; Hoffer et al. 1989; Maas et al. 2009). Soleus fascicles, alternatively, lengthen in early stance (Fig. 9.8C, D), which should cause spindle stretching. Length-sensitive group Ia and II afferents from the triceps surae do increase their activity during early stance in freely walking cats (Loeb and Duysens 1979; Prochazka et al. 1977), however it is not known whether the recordings were made from soleus or gastrocnemius.

Removing group Ib afferent input from soleus and gastrocnemius muscles in the Markin et al. model sharply increases stance duration and causes loss of walking stability within 3 strides (Fig. 9.9C2). Muscle load-dependent sensory signals from ankle extensors thus appear important for maintaining stable walking (see also Ekeberg and Pearson 2005). Load-dependent signals from cat paw pad cutaneous afferents also appear important for promoting extensor activity during the extensor (stance) phase and for controlling phase transitions by resetting the locomotor rhythm (McCrea 2001; Rybak et al. 2006b).

*Afferent Activity during Cat Locomotion* The data presented above were obtained from experimental or computational manipulations of sensory feedback and analysis of the resulting changes in motorneuron or muscle activity. Additional insight into the role of sensory feedback in controlling locomotion can be gained from analysis of afferent activity in freely moving cats. These recordings are typically made from dorsal root ganglia using implanted wire electrodes (Loeb et al. 1977; Prochazka et al. 1977) or an electrode array (Weber et al. 2007). Figure 9.10 shows the activity of muscle





**Figure 9.10** Ensemble activity of cat hindlimb muscle and paw cutaneous afferents during the walk cycle. (A) Each panel is mean *in vivo* recorded muscle EMGs, muscle-tendon unit lengths, and firing rates of group Ia, II, and Ib afferents from nine cat hindlimb muscles. The number of afferents contributing to each trace is shown in parentheses to the left of the traces. Question marks indicate that afferent activity was not recorded. (B1, B2) Activity of individual hair-cell receptors, recorded from L7 and S1 dorsal root ganglia, respectively, with receptive fields on the paw shown by arrows at right. (B3) Activity of a cat paw stretch-sensitive mechanoreceptor. Cell receptive field shown at right. Horizontal bars under traces indicate stance phase of walking. Adapted from Prochazka and Gorassini (1998), B1 and B2 from Loeb et al. (1977), B3 from Loeb (1981), all with permission.

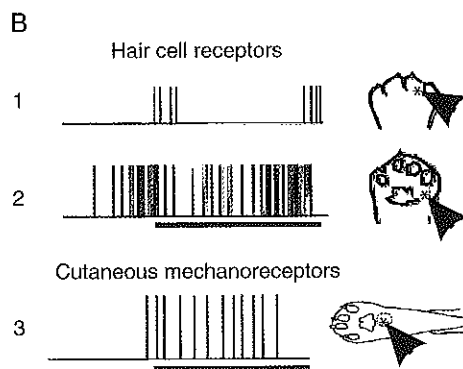


Figure 9.10 (Continued)

length-sensitive spindle group Ia and II afferents and muscle force-sensitive Golgi tendon organ group Ib afferents from nine cat hindlimb muscles and the activity of three skin pressure mechanoreceptors from the paw (Loeb et al. 1977; Prochazka and Gorassini 1998). Activity of Ia and II spindle afferents from ankle flexors—tibialis anterior, extensor digitorum longus, peroneus longus—reaches peak values at stance end. This is consistent with their length changes during walking and the proposed role of this sensory feedback in triggering the stance-swing transition (Hiebert et al. 1996).

Activity of group II spindle afferents from a hip flexor sartorius is also close to maximum at stance end when the muscle-tendon unit length approaches its peak. This feedback again appears to help reset locomotor activity from extension to flexion (Hiebert et al. 1996; Kriellaars et al. 1994). Activity of length sensitive spindle group Ia and II afferents from hip extensor posterior hamstrings increases monotonically during swing and reaches maximum values before stance onset (Fig. 9.10A). This activity is consistent with length sensitive afferents from hip extensors triggering the swing-to-stance transition (McVea et al. 2005) and the earlier onset of extensor muscle activity during downslope walking compared to level or upslope walking (Gregor et al. 2006). Group Ib afferents from ankle extensors—triceps surae, plantaris, and flexor digitorum longus (Fig. 9.10A)—and paw plantar cutaneous mechanoreceptors (Fig. 9.10B) are active during stance and thus could enhance extensor activity during stance and contribute to flexor phase onset at stance end when their activity decreases (McCrea and Rybak 2008; Pearson 2008). Some of the somatosensory activity recorded during free movements and shown in Fig. 9.10 can be substantially depressed by phasic and tonic pre-synaptic inhibition. Specifically, synaptic transmission from group Ia afferents to motorneurons and interneurons is reduced during locomotion compared to rest (Duenas and Rudomin 1988; Gosgnach et al. 2000).

The above account shows that very similar problems confront the use of feedback to control posture and locomotion in arthropods and vertebrates, and evolution has responded with very similar mechanisms. Both groups employ efferent-controlled muscle receptors (MROs and muscle spindles) as key parts of negative feedback PID controllers to stabilize posture. Both use multiple other sensors to provide needed information for feedback control. Both use positive feedback embedded within negative feedback systems to speed locomotory phase transitions. The positive feedback is produced by reversing resistance reflexes to become assistance reflexes. Vertebrates and arthropods accomplish this by pre-synaptically inhibiting afferent terminals onto

motor antagonists with PAD, and by disinhibiting di- and polysynaptic pathways to motor agonists. Phase transitions within a cycle are accomplished through sensory feedback, often mediated by assistance reflexes, that resets the rhythm. It is likely that more complex patterns of control, which may include feed-forward models, prediction of reafference and efference copy (Franklin and Wolpert 2011), are realized by similar mechanisms in arthropods and vertebrates.

## 9.7 Conclusions

The descriptions of the role of sensory feedback in posture and locomotion given above illustrate how complex these systems are and how difficult it is to obtain a comprehensive understanding of how they work in any one animal. This difficulty also stems from the experimental necessity of focusing on individual elements and how they contribute to the function of small parts of the system or the entire system itself, as seen through the animal's behavior. The role of individual sense organs, or of particular network elements, in locomotion and posture is difficult to determine because of the many simultaneous interactions that occur among the parts of the system in any one state, and because of the transformations in those interactions caused by changes in system state. These difficulties beg the question of how to understand feedback in the context of the entire system as the animal adopts particular postures, shifts from posture to walking, and changes gait or direction.

Since the work of Hodgkin and Huxley (1952), computational models have been used to describe dynamic relationships among the elements of complex neural systems. Such approaches are particularly helpful for understanding sensorimotor integration and complex motor systems and movements (Bacque-Cazenave et al. 2015; Chiel et al. 2009; Cofer et al. 2010b; Ekeberg et al. 2004; Ekeberg and Grillner 1999; Markin et al. 2016; Pearson et al. 2006; Shadmehr and Wise 2005). Most models are built to account for specific, limited sets of phenomena seen in experiments or displayed by the animal under well-defined conditions. They capture the properties of specific network elements, sensory receptors, or muscle and limb biomechanics, and ask whether and over what range of parameter values their interaction can account for emergent properties of the system. When such models fail they are useful because they demonstrate gaps in our understanding. Interrogating the model can then suggest how those gaps might be filled through new experiments or by changes in the model. When they succeed they are useful because they provide insights into how adaptive properties emerge from the system and can be used to simulate future experiments that provide new tests of the model.

We believe, however, that models attempting to reconstruct the entire system governing an animal's postural and locomotor behavior are also needed. Such models would include the musculoskeletal structure of the animal, its relevant sense organs, sensory afferents, local networks, and descending inputs. It must also include relevant portions of the physical environment: ground and water surfaces, gravity, surface friction, hydrodynamics. These models would not replace models focused on understanding particular aspects of a system, such as specific network configurations (Fig. 9.7) or biophysical details (De et al. 2005). They would also not replace top-down models that capture overall postural or locomotor behavior (Ekeberg 1993, 2004). Rather, they would enable



relevant aspects of these models to be incorporated into an overarching model that would reveal how their dynamic interactions contribute to behavior.

Building an entire system model is substantially easier in arthropods, with 1,000 neurons in each segmental ganglion and 95 leg motor neurons (Cattaert 2014), than in vertebrates, where the numbers are many thousands time larger. However, even for an arthropod this is not a task that a single research team can do. It is rather the task of a community of researchers, each of whom contributes to the parts of the system she or he knows best. Each addition creates opportunities for examining previously unexamined interactions. For example, adding visual systems to a model of motor control creates an opportunity to investigate visually guided motor control.

This presupposes a common modeling environment in which community members have access to the relevant set of published models and can build on or revise them. It also assumes that the model becomes a knowledge base, in which each model part—neuron, synapse, muscle, sense organ—is linked to the source publications of the part. These annotations identify the experimental contexts from which model parameter values were obtained, and so identify the contexts in which simulations are valid. Such a model would provide a statement of what is currently understood about an animal, a statement that would be continually revised in light of new experimental knowledge, computational capabilities, and tests of model validity.

## Acknowledgements

Support was provided by NSF Grant IOS1120291 to DHE and NIH grants NS-048844, EB-012855, HD032571, and support from the Center for Human Movement Studies, Georgia Tech, to BIP.

## Endnote

- 1 The lower case "f" in "fCO" distinguishes the femoral chordotonal organ of insects from the "FCO", the funnel canal organ of Crustacea, with a capital "F".

## References

- Abelew TA, Miller MD, Cope TC, Nichols TR (2000) Local loss of proprioception results in disruption of interjoint coordination during locomotion in the cat. *J Neurophysiol* 84:2709–2714.
- Abraira VE, Ginty DD (2013) The sensory neurons of touch. *Neuron* 79:618–639.
- Akay T, Büschges A (2006) Load signals assist the generation of movement dependent reflex reversal in the femur–tibia joint of stick insects. *J Neurophysiol* 96:3532–3537.
- Alvarez FJ, Bullinger KL, Titus HE, Nardelli P, Cope TC (2010) Permanent reorganization of Ia afferent synapses on motoneurons after peripheral nerve injuries. *Ann NY Acad Sci* 1198:231–241.
- An KN, Takahashi K, Harrigan TP, Chao EY (1984) Determination of muscle orientations and moment arms. *J Biomech Eng* 106:280–282.

- Andersson O, Grillner S (1983) Peripheral control of the cat's step cycle. II. Entrainment of the central pattern generators for locomotion by sinusoidal hip movements during "fictive locomotion.". *Acta Physiol Scand* 118:229–239.
- Bacque-Cazenave J, Chung BP, Cofer D, Cattaert D, Edwards DH (2015) The effect of sensory feedback on crayfish posture and locomotion: II. Neuromechanical simulation of closing the loop *J Neurophysiol* 113:1772–1783.
- Bässler U (1976) Reversal of a reflex to a single motoneuron in the stick insect *Carausius morosus*. *Biol Cyber* 24:47–49.
- Bässler U (1993) The femur–tibia control system of stick insects—a model for the study of the neural basis of joint control. *Brain Res Rev* 18:207–226.
- Bender JA, Pollack AJ, Ritzmann RE (2010) Neural activity in the central complex of the insect brain is linked to locomotor changes. *Curr Biol* 20:921–926.
- Bennett DJ, De Serres SJ, Stein RB (1996) Gain of the triceps surae stretch reflex in decerebrate and spinal cats during postural and locomotor activities. *J Physiol* 496:837–850.
- Bowerman RF, Larimer JL (1974a) Command fibres in the circumoesophageal connectives of crayfish. I. Tonic fibres. *J Exp Biol* 60:95–11.
- Bowerman RF, Larimer JL (1974b) Command fibres in the circumoesophageal connectives of crayfish. II. Phasic fibres. *J Exp Biol* 60:119–134.
- Brown TG (1911) The intrinsic factors in the act of progression in the mammal. *Proc R Soc Lond* 84:308–319.
- Bullinger KL, Nardelli P, Pinter MJ, Alvarez FJ, Cope TC (2011) Permanent central synaptic disconnection of proprioceptors after nerve injury and regeneration. II. Loss of functional connectivity with motoneurons. *J Neurophysiol* 106:2471–2485.
- Bunderson NE, McKay JL, Ting LH, Burkholder TJ (2010) Directional constraint of endpoint force emerges from hindlimb anatomy. *J Exp Biol* 213:2131–2141.
- Burrows M (1996) *The Neurobiology of an Insect Brain*. Oxford, UK: Oxford University Press.
- Burrows M, Laurent G (1993) Synaptic potentials in the central terminals of locust proprioceptive afferents generated by other afferents from the same sense organ. *J Neurosci* 13:808–819.
- Burrows M, Laurent GJ, Field LH (1988) Proprioceptive inputs to nonspiking local interneurons contribute to local reflexes of a locust hindleg. *J Neurosci* 8:3085–3093.
- Büschges A (2012) Lessons for circuit function from large insects: towards understanding the neural basis of motor flexibility. *Curr Opin Neurobiol* 22:602–608.
- Büschges A, Scholz H, El Manera A (2011) New moves in motor control. *Curr Biol* 21:R513–R524.
- Büschges A, Wolf H (1999) Phase-dependent pre-synaptic modulation of mechanosensory signals in the locust flight system. *J Neurophysiol* 81:959–962.
- Cattaert D (2014) Neural control of posture and walking in crustaceans. *In Crustacean Nervous Systems and Their Control of Behavior*, Derby CD, Thiel M (eds). Oxford, UK: Oxford University Press.
- Cattaert D, El Manira A (1999) Shunting versus inactivation: analysis of pre-synaptic inhibitory mechanisms in primary afferents of the crayfish. *J Neurosci* 19:6079–6089.
- Cattaert D, El Manira A, Bevingut M (1999) Pre-synaptic inhibition and antidromic discharges in crayfish primary afferents. *J Physiol Paris* 93:349–358.

- Cattaert D, El Manira A, Clarac F (1992) Direct evidence for pre-synaptic inhibitory mechanisms in crayfish sensory afferents. *J Neurophysiol* 67:610–624.
- Cattaert D, Le Ray D (2001) Adaptive motor control in crayfish. *Prog Neurobiol* 63:199–240.
- Chiel HJ, Ting LH, Ekeberg O, Hartmann MJ (2009) The brain in its body: motor control and sensing in a biomechanical context. *J Neurosci* 29:12807–12814.
- Chrachri A, Clarac F (1989) Synaptic connections between motor neurons and interneurons in the fourth thoracic ganglion of the crayfish, *Procambarus clarkii*. *J Neurophysiol* 62:1237–1250.
- Chung B, Bacque-Cazenave J, Cattaert D, Edwards DH (2015) The effect of sensory feedback on crayfish posture and locomotion: I. Experimental analysis of closing the loop. *J Neurophysiol* 113:1763–1771.
- Clarac F (2008) Some historical reflections on the neural control of locomotion. *Brain Res Rev* 57:13–21.
- Clarac F, Cattaert D (1996) Invertebrate pre-synaptic inhibition and motor control. *Exp Brain Res* 112:163–180.
- Clarac F, Chrachri A, Cattaert D (1991) Interneuronal control of a walking leg reflex in an *in vitro* crayfish preparation. In *Locomotor Neural Mechanism in Arthropods and Vertebrates*, Armstrong DM, Bush BMH (eds). Manchester, UK: Manchester University Press.
- Clarac F, Pearlstein E (2007) Invertebrate preparations and their contribution to neurobiology in the second half of the 20th century. *Brain Res Rev* 54:113–161.
- Clarac F, Vedel JP, Bush BM (1978) Intersegmental reflex coordination by a single joint receptor organ (CB) in rock lobster walking legs. *J Exp Biol* 73:29–46.
- Cofer D, Cymbalyuk G, Reid J, Zhu Y, et al. (2010a) AnimatLab: A 3D graphics environment for neuromechanical simulations. *J Neurosci Methods* 187:280–288.
- Cofer DW, Cymbalyuk G, Heitler WJ, Edwards DH (2010b) Neuromechanical simulation of the locust jump. *J Exp Biol* 213:1060–1068.
- Cope TC, Bonasera SJ, Nichols TR (1994) Reinnervated muscles fail to produce stretch reflexes. *J Neurophysiol* 71:817–820.
- Cope TC, Clark BD (1993) Motor-unit recruitment in self-reinnervated muscle. *J Neurophysiol* 70:1787–1796.
- Day JT, Lichtwark GA, Cresswell AG (2013) Tibialis anterior muscle fascicle dynamics adequately represent postural sway during standing balance. *J Appl Physiol* 115:1742–1750.
- De SE, Ekeberg O, Kotaleski JH, Achard P, Lansner A (2005) Biophysically detailed modelling of microcircuits and beyond. *Trends Neurosci* 28:562–569.
- Derby CD, Thiel M editors (2010) *Crustacean Nervous Systems and Control of Behavior*. Oxford, UK: Oxford University Press.
- DiCaprio RA, Clarac F (1981) Reversal of a walking leg reflex elicited by a muscle receptor. *J Exp Biol* 90:197–203.
- DiCaprio RA, Clarac F (1983) Reversal of an intersegmental reflex elicited by a muscle receptor organ. *J Exp Biol* 103:303–306.
- Duenas SH, Rudomin P (1988) Excitability changes of ankle extensor group Ia and Ib fibers during fictive locomotion in the cat. *Exp Brain Res* 70:15–25.
- Duysens J, Clarac F, Cruse H (2000) Load-regulating mechanisms in gait and posture: comparative aspects. *Physiol Rev* 80:83–133.



- Duysens J, Pearson KG (1980) Inhibition of flexor burst generation by loading ankle extensor muscles in walking cats. *Brain Res* 187:321–332.
- Eccles JC, Magni F, Willis WD (1962) Depolarization of central terminals of group I afferent fibres from muscle. *J Physiol* 160:62–93.
- Edwards DH (1990) Mechanisms of depolarizing inhibition at the crayfish giant motor synapse. I. Electrophysiology. *J Neurophysiol* 64:532–540.
- Ekeberg O (1993) A combined neuronal and mechanical model of fish swimming. *Biol Cybern* 69:373–374.
- Ekeberg O, Blumel M, Büschges A (2004) Dynamic simulation of insect walking. *Arthropod Struct Dev* 33:287–300.
- Ekeberg O, Grillner S (1999) Simulations of neuromuscular control in lamprey swimming. *Philos Trans R Soc Lond B* 354:895–902.
- Ekeberg O, Pearson K (2005) Computer simulation of stepping in the hind legs of the cat: an examination of mechanisms regulating the stance-to-swing transition. *J Neurophysiol* 94:4256–4268.
- El Manira A, Cattaert D, Clarac F (1991a) Monosynaptic connections mediate resistance reflex in crayfish (*Procambarus clarkii*) walking legs. *J Comp Physiol A* 168:1432–1351.
- El Manira A, DiCaprio RA, Cattaert D, Clarac F (1991b) Monosynaptic interjoint reflexes and their central modulation during fictive locomotion in crayfish. *Eur J Neurosci* 3:1219–1231.
- Eng JJ, Hoffer JA (1997) Regional variability of stretch reflex amplitude in the cat medial gastrocnemius muscle during a postural task. *J Neurophysiol* 78:1150–1154.
- Evoy WH, Ayers J (1982) Locomotion and control of limb movements. *In* *Neural Integration and Behavior*, Sandeman DC, Atwood HL (eds). New York, NY: Academic Press.
- Feldman AG, Orlovsky GN (1975) Activity of interneurons mediating reciprocal Ia inhibition during locomotion. *Brain Res* 84:181–194.
- Fink AJ, Croce KR, Huang ZJ, Abbott LF, et al. (2014) Pre-synaptic inhibition of spinal sensory feedback ensures smooth movement. *Nature* 509:43–48.
- Flitney FW, Hirst DG (1978) Cross-bridge detachment and sarcomere 'give' during stretch of active frog's muscle. *J Physiol* 276:449–465.
- Franklin DW, Wolpert DM (2011) Computational mechanisms of sensorimotor control. *Neuron* 72:425–442.
- Gabriel JP, Büschges A (2007) Control of stepping velocity in a single insect leg during walking. *Phil Trans R Soc A* 365:251–271.
- Gosgnach S, Quevedo J, Fedirchuk B, McCrea DA (2000) Depression of group Ia monosynaptic EPSPs in cat hindlimb motoneurons during fictive locomotion. *J Physiol* 526:639–652.
- Gossard JP, Bouyer L, Rossignol S (1999) The effects of antidromic discharges on orthodromic firing of primary afferents in the cat. *Brain Res* 825:132–145.
- Gossard JP, Brownstone RM, Barajon I, Hultborn H (1994) Transmission in a locomotor-related group Ib pathway from hindlimb extensor muscles in the cat. *Exp Brain Res* 98:213–228.
- Govind CK, Atwood HL (1982) Organization of neuromuscular systems. *In* *The Biology Of Crustacea. Volume 3: Neurobiology, Structure and Function*. Bliss DE, Sandeman DC, Atwood HL (eds). Waltham, MA: Academic Press.
- Gray J (1968) *Animal locomotion*. London, UK: William Clowes & Sons.

- Gregor RJ, Bulgakova MA, Maas H, Oliver A, Prilutsky BI (2014) Locomotor activity of feline ankle extensors and kinematics during level and slope walking after removal of stretch reflex from soleus and lateral gastrocnemius by self-reinnervation. Program No. 827.01. Soc Neurosci Abstr. Online.
- Gregor RJ, Smith DW, Prilutsky BI (2006) Mechanics of slope walking in the cat: quantification of muscle load, length change, and ankle extensor EMG patterns. *J Neurophysiol* 95:1397–1409.
- Griffiths RI (1991) Shortening of muscle fibres during stretch of the active cat medial gastrocnemius muscle: the role of tendon compliance. *J Physiol* 436:219–236.
- Gross CG (1998) Claude Bernard and the Constancy of the Internal Environment. *Neuroscientist* 4:380–385.
- Guertin P, Angel MJ, Perreault MC, McCrea DA (1995) Ankle extensor group I afferents excite extensors throughout the hindlimb during fictive locomotion in the cat. *J Physiol* 487:197–209.
- Hartman HB (1985) Tension receptors on the closer muscle apodeme in the walking legs of the blue crab, *Callinectes sapidus*. *J Comp Physiol* 157:355–362.
- Head SI, Bush BMH (1991) Reflex actions of one proprioceptor on the motoneurons of a muscle receptor and their central modulation in the shore crab. *J Physiol* 437:49–62.
- Hellekes K, Blincow E, Hoffmann J, Büschges A (2012) Control of reflex reversal in stick insect walking: effects of intersegmental signals, changes in direction, and optomotor-induced turning. *J Neurophysiol* 107:239–249.
- Henry SM, Fung J, Horak FB (1998) EMG responses to maintain stance during multidirectional surface translations. *J Neurophysiol* 80:1939–1950.
- Hiebert GW, Whelan PJ, Prochazka A, Pearson KG (1996) Contribution of hind limb flexor muscle afferents to the timing of phase transitions in the cat step cycle. *J Neurophysiol* 75:1126–1137.
- Hodgkin AL, Huxley AF (1952) A quantitative description of membrane current and its application to conduction and excitation in nerve. *J Physiol (London)* 117:500–544.
- Hof AL, Gazendam MG, Sinke WE (2005) The condition for dynamic stability. *J Biomech* 38:1–8.
- Hoffer JA, Caputi AA, Pose IE, Griffiths RI (1989) Roles of muscle activity and load on the relationship between muscle spindle length and whole muscle length in the freely walking cat. *Prog Brain Res* 80:75–85.
- Hogan N (1985) The mechanics of multi-joint posture and movement control. *Biol Cybern* 52:315–331.
- Honeycutt CF, Nardelli P, Cope TC, Nichols TR (2012) Muscle spindle responses to horizontal support surface perturbation in the anesthetized cat: insights into the role of autogenic feedback in whole body postural control. *J Neurophysiol* 108:1253–1261.
- Honeycutt CF, Nichols TR (2010) Disruption of cutaneous feedback alters magnitude but not direction of muscle responses to postural perturbations in the decerebrate cat. *Exp Brain Res* 203:765–771.
- Honeycutt CF, Nichols TR (2014) The mechanical actions of muscles predict the direction of muscle activation during postural perturbations in the cat hindlimb. *J Neurophysiol* 111:900–907.

- Horak FB, Macpherson JM (2011) Postural orientation and equilibrium. *Comp Physiol, Supplement 29: Handbook of Physiology, Exercise: Regulation and Integration of Multiple Systems*:255–292. First published in print. doi: 101002/cphycp120107.
- Hulliger M, Durmuller N, Prochazka A, Trend P (1989) Flexible fusimotor control of muscle spindle feedback during a variety of natural movements. *Prog Brain Res* 80:87–101.
- Hunt CC (1990) Mammalian muscle spindle: peripheral mechanisms. *Physiol Rev* 70:643–663.
- Huyghues-Despointes CM, Cope TC, Nichols TR (2003) Intrinsic properties and reflex compensation in reinnervated triceps surae muscles of the cat: effect of activation level. *J Neurophysiol* 90:1537–1546.
- Jacobs R, Macpherson JM (1996) Two functional muscle groupings during postural equilibrium tasks in standing cats. *J Neurophysiol* 76:2402–2411.
- Jami L (1992) Golgi tendon organs in mammalian skeletal muscle: functional properties and central actions. *Physiol Rev* 72:623–666.
- Jeka JJ, Lackner JR (1994) Fingertip contact influences human postural control. *Exp Brain Res* 100:495–502.
- Joyce GC, Rack PM, Westbury DR (1969) The mechanical properties of cat soleus muscle during controlled lengthening and shortening movements. *J Physiol* 204:461–474.
- Kagaya K, Takahata M (2011) Sequential synaptic excitation and inhibition shape readiness discharge for voluntary behavior. *Science* 332:365–368.
- Kennedy D, Calabrese RL, Wine JJ (1974) Pre-synaptic inhibition: primary afferent depolarization in crayfish neurons. *Science* 186:451–454.
- Klarner D, Barth FG (1986) The cuticular stress detector (CSD2) of the crayfish. I. Physiological properties. *J Exp Biol* 122:149–159.
- Kriellaars DJ, Brownstone RM, Noga BR, Jordan LM (1994) Mechanical entrainment of fictive locomotion in the decerebrate cat. *J Neurophysiol* 71:2074–2086.
- Lam T, Pearson KG (2001) Proprioceptive modulation of hip flexor activity during the swing phase of locomotion in decerebrate cats. *J Neurophysiol* 86:1321–1332.
- Lam T, Pearson KG (2002) Sartorius muscle afferents influence the amplitude and timing of flexor activity in walking decerebrate cats. *Exp Brain Res* 147:175–185.
- Landsmeer JM (1961) Studies in the anatomy of articulation. I. The equilibrium of the “intercalated” bone. *Acta Morphol Neerl Scand* 3:287–303.
- Laurent G, Burrows M (1989) Intersegmental interneurons can control the gain of reflexes in adjacent segments of the locust by their action on nonspiking local interneurons. *J Neurosci* 9:3030–3039.
- Le Bon-Jego M, Masante-Roca I, Cattaert D (2006) State-dependent regulation of sensory–motor transmission: role of muscarinic receptors in sensory–motor integration in the crayfish walking system. *Eur J Neurosci* 23:1283–1300.
- Le Ray D, Cattaert D (1997) Neural mechanisms of reflex reversal in coxo-basipodite depressor motor neurons of the crayfish. *J Neurophysiol* 77:1963–1978.
- Leibrock CS, Marchand AR, Barnes WJ, Clarac F (1996) Synaptic connections of the cuticular stress detectors in crayfish: mono- and polysynaptic reflexes and the entrainment of fictive locomotion in an *in vitro* preparation. *J Comp Physiol A* 178:711–725.
- Li Y, Levine WS, Loeb GE (2012) A two-joint human posture control model with realistic neural delays. *IEEE T Neural Sys Reh* 20:738–748.



- Libersat F, Clarac F, Zill S (1987a) Force-sensitive mechanoreceptors of the dactyl of the crab: single-unit responses during walking and evaluation of function. *J Neurophysiol* 57:1618–1637.
- Libersat F, Zill S, Clarac F (1987b) Single-unit responses and reflex effects of force-sensitive mechanoreceptors of the dactyl of the crab. *J Neurophysiol* 57:1601–1617.
- Loeb GE (1981) Somatosensory unit input to the spinal cord during normal walking. *Can J Physiol Pharmacol* 59:627–635.
- Loeb GE, Bak MJ, Duysens J (1977) Long-term unit recording from somatosensory neurons in the spinal ganglia of the freely walking cat. *Science* 197:1192–1194.
- Loeb GE, Duysens J (1979) Activity patterns in individual hindlimb primary and secondary muscle spindle afferents during normal movements in unrestrained cats. *J Neurophysiol* 42:420–440.
- Loram ID, Maganaris CN, Lakie M (2005) Human postural sway results from frequent, ballistic bias impulses by soleus and gastrocnemius. *J Physiol* 564:295–311.
- Loram ID, Maganaris CN, Lakie M (2009) Paradoxical muscle movement during postural control. *Med Sci Sports Exerc* 41:198–204.
- Lyle MA, Prilutsky BI, Gregor RJ, Abelew TA, Nichols TR (2016) Self-reinnervated muscles lose autogenic length feedback, but intermuscular feedback can recover functional connectivity. *J Neurophysiol* 116:1055–1067.
- Maas H, Gregor RJ, Hodson-Tole EF, Farrell BJ, Prilutsky BI (2009) Distinct muscle fascicle length changes in feline medial gastrocnemius and soleus muscles during slope walking. *J Appl Physiol* 106:1169–1180.
- Maas H, Prilutsky BI, Nichols TR, Gregor RJ (2007) The effects of self-reinnervation of cat medial and lateral gastrocnemius muscles on hindlimb kinematics in slope walking. *Exp Brain Res* 181:377–393.
- Macpherson JM (1988a) Strategies that simplify the control of quadrupedal stance. I. Forces at the ground. *J Neurophysiol* 60:204–217.
- Macpherson JM (1988b) Strategies that simplify the control of quadrupedal stance. II. Electromyographic activity. *J Neurophysiol* 60:218–231.
- Macpherson JM, Fung J (1999) Weight support and balance during perturbed stance in the chronic spinal cat. *J Neurophysiol* 82:3066–3081.
- Malamud JG, Godt RE, Nichols TR (1996) Relationship between short-range stiffness and yielding in type-identified, chemically skinned muscle fibers from the cat triceps surae muscles. *J Neurophysiol* 76:2280–2289.
- Malone LA, Bastian AJ (2010) Thinking about walking: effects of conscious correction versus distraction on locomotor adaptation. *J Neurophysiol* 103:1954–1962.
- Marchand AR, Barnes WJ, Cattaert D (1997) Primary afferent depolarizations of sensory origin within contact-sensitive mechanoreceptive afferents of a crayfish leg. *J Neurophysiol* 77:3340–3354.
- Markin SN, Klishko AN, Shevtsova NA, Lemay MA, et al. (2010) Afferent control of locomotor CPG: insights from a simple neuromechanical model. *Ann NY Acad Sci* 1198:21–34.
- Markin SN, Klishko AN, Shevtsova NA, Lemay MA, et al. (2016) A neuromechanical model of spinal control of locomotion. *In* *Neuromechanical Modeling of Posture and Locomotion*. Prilutsky BI, Edwards DH Jr, (eds). New York, NY: Springer.

- Masani K, Vette AH, Popovic MR (2006) Controlling balance during quiet standing: proportional and derivative controller generates preceding motor command to body sway position observed in experiments. *Gait Posture* 23:164–17.
- Matthews PB (1981) Evolving views on the internal operation and functional role of the muscle spindle. *J Physiol* 320:1–30.
- Maxwell JC (1868) On governors. *Proc R Soc Lond* 16:270–283.
- Mazzaro N, Grey MJ, Sinkjaer T (2005) Contribution of afferent feedback to the soleus muscle activity during human locomotion. *J Neurophysiol* 93:167–177.
- McCrea DA (2001) Spinal circuitry of sensorimotor control of locomotion. *J Physiol* 533:41–50.
- McCrea DA, Rybak IA (2008) Organization of mammalian locomotor rhythm and pattern generation. *Brain Res Rev* 57:134–146.
- McVea DA, Donelan JM, Tachibana A, Pearson KG (2005) A role for hip position in initiating the swing-to-stance transition in walking cats. *J Neurophysiol* 94:3497–3508.
- Mehta R, Kajtaz E, Gregor RJ, Prilutsky BI (2014) Effects of stretch-reflex removal by self-reinnervation of one-joint vastii and two-joint rectus femoris on hindlimb muscle activity and mechanics during walking in the cat. Program No. 734.06. Soc Neurosci Abstr. Online.
- Mehta R, Prilutsky BI (2014) Task-dependent inhibition of slow-twitch soleus and excitation of fast-twitch gastrocnemius do not require high movement speed and velocity-dependent sensory feedback. *Front Physiol* 5:410.
- Meyer PF, Oddsson LI, De Luca CJ (2004) Reduced plantar sensitivity alters postural responses to lateral perturbations of balance. *Exp Brain Res* 157:526–536.
- Mill PJ (1976) Structure and function of proprioceptors in the invertebrates. London, UK: Chapman and Hall.
- Misiaszek JE (2003) The H-reflex as a tool in neurophysiology: its limitations and uses in understanding nervous system function. *Muscle Nerve* 28:144–160.
- Muller U, Clarac F (1990) Dactyl sensory influences on rock lobster locomotion. II. Role in interleg coordination. *J Exp Biol* 148:113–128.
- Mussa-Ivaldi FA, Hogan N, Bizzi E (1985) Neural, mechanical, and geometric factors subserving arm posture in humans. *J Neurosci* 5:2732–2743.
- Nashner LM, Shupert CL, Horak FB, Black FO (1989) Organization of posture controls: an analysis of sensory and mechanical constraints. *Prog Brain Res* 80:411–418.
- Newland PL, Emptage NJ (1996) The central connections and actions during walking of tibial campaniform sensilla in the locust. *J Comp Physiol* 178:749–762.
- Nichols TR, Houk JC (1976) Improvement in linearity and regulation of stiffness that results from actions of stretch reflex. *J Neurophysiol* 39:119–142.
- Niven JE, Graham CM, Burrows M (2008) Diversity and evolution of the insect ventral nerve cord. *Annu Rev Entomol* 53:253–271.
- Pantall A, Gregor RJ, Mehta R, Prilutsky BI (2014) Effects of 60-min sciatic nerve stimulation immediately after cut and repair of feline soleus and lateral gastrocnemius nerves on locomotor EMG activity of ankle muscles. Program No. 539.19. Soc Neurosci Abstr. Online.
- Pantall A, Hodson-Tole EF, Gregor RJ, Prilutsky BI (2016) Increased intensity and reduced frequency of EMG signals from feline self-reinnervated ankle extensors during walking do not normalize excessive lengthening. *J Neurophysiol* 115:2406–2420.

- Pearson K, Ekeberg O, Büschges A (2006) Assessing sensory function in locomotor systems using neuro-mechanical simulations. *Trends Neurosci* 29:625–631.
- Pearson KG (1972) Central programming and reflex control of walking in the cockroach. *J Exp Biol* 56:173–193.
- Pearson KG (2008) Role of sensory feedback in the control of stance duration in walking cats. *Brain Res Rev* 57:222–227.
- Perreault MC, Angel MJ, Guertin P, McCrea DA (1995) Effects of stimulation of hindlimb flexor group II afferents during fictive locomotion in the cat. *J Physiol* 487:211–220.
- Peterka RJ (2002) Sensorimotor integration in human postural control. *J Neurophysiol* 88:1097–1118.
- Prilutsky BI, Klishko AN, Weber DJ, Lemay MA (2016) Computing motion dependent afferent activity during cat locomotion using a forward dynamics musculoskeletal model. *In* *Neuromechanical Modeling of Posture and Locomotion*. Prilutsky BI, Edwards DH Jr, (eds). New York, NY: Springer.
- Prochazka A (1996) Proprioceptive feedback and movement regulation. *In* *Handbook of Physiology Section 12: Exercise and Regulation of Multiple Systems*. Rowell LB, Shepherd JT (eds). Bethesda, MD: American Physiological Society.
- Prochazka A, Gorassini M (1998) Ensemble firing of muscle afferents recorded during normal locomotion in cats. *J Physiol* 507:293–304.
- Prochazka A, Westerman RA, Ziccone SP (1977) Ia afferent activity during a variety of voluntary movements in the cat. *J Physiol* 268:423–448.
- Rack PM, Westbury DR (1969) The effects of length and stimulus rate on tension in the isometric cat soleus muscle. *J Physiol* 204:443–460.
- Rack PM, Westbury DR (1974) The short range stiffness of active mammalian muscle and its effect on mechanical properties. *J Physiol* 240:331–350.
- Ritzmann RE, Harley CM, Daltorio KA, Tietz BR, et al. (2012) Deciding which way to go: how do insects alter movements to negotiate barriers? *Front Neurosci* 6:97.
- Rybak IA, Shevtsova NA, Lafreniere-Roula M, McCrea DA (2006a) Modelling spinal circuitry involved in locomotor pattern generation: insights from deletions during fictive locomotion. *J Physiol* 577:617–639.
- Rybak IA, Stecina K, Shevtsova NA, McCrea DA (2006b) Modelling spinal circuitry involved in locomotor pattern generation: insights from the effects of afferent stimulation. *J Physiol* 577:641–658.
- Safavynia SA, Ting LH (2013) Long-latency muscle activity reflects continuous, delayed sensorimotor feedback of task-level and not joint-level error. *J Neurophysiol* 110:1278–1290.
- Schmitz J (1993) Load-compensating reactions in the proximal leg joints of stick insects during standing and walking. *J Exp Biol* 183:15–33.
- Shadmehr R, Wise SP (2005) *The Computational Neurobiology of Reaching and Pointing*. Cambridge, MA: MIT Press.
- Sherrington CS (1910) Flexion–reflex of the limb, crossed extension–reflex, and reflex stepping and standing. *J Physiol* 40:28–121.
- Sherrington CS (1913) Further observations on the production of reflex stepping by combination of reflex excitation with reflex inhibition. *J Physiol* 47:196–214.
- Sillar KT, Skorupski P, Elson RC, Bush BMH (1986) Two identified afferent neurones entrain a central locomotor rhythm generator. *Nature* 323:440–443.



- Skorupski P, Rawat BM, Bush BM (1992) Heterogeneity and central modulation of feedback reflexes in crayfish motor pool. *J Neurophysiol* 67:648–663.
- Skorupski P, Sillar KT (1986) Phase-dependent reversal of reflexes mediated by the thoracocoxal muscle receptor organ in the crayfish, *Pacifastacus leniusculus*. *J Neurophysiol* 55:689–695.
- Smith JL, Zernicke RF (1987) Predictions for neural control based on limb dynamics. *Trends Neurosci* 10:123–128.
- Stapley PJ, Ting LH, Hulliger M, Macpherson JM (2002) Automatic postural responses are delayed by pyridoxine-induced somatosensory loss. *J Neurosci* 22:5803–5807.
- Stein RB, Capaday C (1988) The modulation of human reflexes during functional motor tasks. *Trends Neurosci* 11:328–332.
- Stein RB, Misiaszek JE, Pearson KG (2000) Functional role of muscle reflexes for force generation in the decerebrate walking cat. *J Physiol* 525:781–791.
- Strausfeld NJ (2012) *Arthropod Brains: Evoluton, Functional Elegance and Historical Significance*. Cambridge, MA: Belknap Press.
- Stuart DG, Hultborn H (2008) Thomas Graham Brown (1882–1965), Anders Lundberg (1920–), and the neural control of stepping. *Brain Res Rev* 59:74–95.
- Taylor A, Durbaba R, Ellaway PH, Rawlinson S (2006) Static and dynamic gamma-motor output to ankle flexor muscles during locomotion in the decerebrate cat. *J Physiol* 571:711–723.
- Torres-Oviedo G, Macpherson JM, Ting LH (2006) Muscle synergy organization is robust across a variety of postural perturbations. *J Neurophysiol* 96:1530–1546.
- von Holst E, Mittelstaedt H (1950) Daz Reafferezprincip. Wechselwirkungen zwischen Zentralnerven-system und Peripherie. *Naturwissenschaften* 37:467–476. Translation: The reafference principle. *In* *The Behavioral Physiology of Animals and Man. The Collected Papers of Erich von Holst* (Translated by Martin R) (1973) Coral Gables, FL: University of Miami Press.
- Watling L, Thiel M (eds). (2013) *Functional Morphology and Diversity*. Oxford, UK: Oxford University Press.
- Weber DJ, Stein RB, Everaert DG, Prochazka A (2007) Limb-state feedback from ensembles of simultaneously recorded dorsal root ganglion neurons. *J Neural Eng* 4:S168–180.
- Wiener N (1961) *Cybernetics: or Control and Communication in the Animal and the Machine*. Cambridge, MA: MIT Press.
- Wiersma CA (1961) Reflexes and the central nervous system. *In* *The Physiology of Crustacea. II Sense Organs, Integration, and Behavior*. Waterman TH (ed). New York, NY: Academic Press.
- Winter DA (1995) Human balance and posture control during standing and walking. *Gait Posture* 3:193–214.
- Yakovenko S, Gritsenko V, Prochazka A (2004) Contribution of stretch reflexes to locomotor control: a modeling study. *Biol Cybern* 90:146–155.
- Zill SN, Keller BR, Chaudhry S, Duke ER, et al. (2010) Detecting substrate engagement: responses of tarsal campaniform sensilla in cockroaches. *J Comp Physiol A* 196:407–420.
- Zill SN, Keller BR, Duke ER (2009) Sensory signals of unloading in one leg follow stance onset in another leg: transfer of load and emergent coordination in cockroach walking. *J Neurophysiol* 101:2297–2304.

Zill SN, Moran DT (1981) The exoskeleton and insect proprioception. I. Responses of tibial campaniform sensilla to external and muscle-generated forces in the American cockroach, *Periplaneta americana*. *J Exp Biol* 91:1–24.

Zill SN, Moran DT, Varela FG (1981) The exoskeleton and insect proprioception: II. Reflex effects of tibial campaniform sensilla in the American cockroach, *Periplaneta americana*. *J Exp Biol* 94:43–55.

Zill SN, Schmitz J, Chaudhry S, Büschges A (2012) Force encoding in stick insect legs delineates a reference frame for motor control. *J Neurophysiol* 108:1453–1472.