

Neurobiology: Reconstructing the Neural Control of Leg Coordination

Walking is adaptable because the timing of movements of individual legs can be varied while maintaining leg coordination. Recent work in stick insects shows that leg coordination set by interactions of pattern generating circuits can be overridden by sensory feedback.

Sasha N. Zill and Bridget R. Keller

The coordination of leg movements for walking in rigid patterns is a relatively simple problem to solve in computer simulations or in legged robots. The phases of leg movement can be preprogrammed like an orchestral score, or legs can be mechanically linked together in groups (a technique used in many toys that walk) [1,2]. Fixed patterns of leg coordination are reliable but not adaptable, and can result in instability if a leg loses contact with the substrate or encounters an obstacle in rough terrain. Humans and other animals, however, can both walk with precise cadences and readily regain coordination if a leg slips or stumbles. The control mechanisms of walking in animals permit individual legs to generate rapid compensatory reactions, often without disrupting the overall patterns of movements in other legs [3].

Adaptable walking in animals requires that the control of leg movements be shared among different neural centers. New insight into how this is accomplished has come from work of Borgmann *et al.* [4] on the mechanisms underlying coordination of leg movements in stick insects. Insects are hexapods with six legs arranged two to a body segment (Figure 1A, left). In walking, the right and left legs of each segment alternate in phase (one leg presses on the substrate in stance when the opposite leg is lifted in swing) [5]. Movements of legs of adjacent segments — for example, the front and middle legs of one side — also alternate in phase so that two neighboring legs are not lifted simultaneously in swing. Previous work has shown that in stick insects, as in many other animals, the timing of leg movements in walking is produced by groups of neurons that form pattern generators within the central nervous system [6].

A single pattern generator produces rhythmic bursting in motor neurons to the muscles in an individual leg

(although the neural circuits also contain individual oscillators for each joint) [7]. In stick insects, the circuitry of the pattern generators for a pair of legs is found within the corresponding thoracic ganglion (Figure 1A, right). Previous experiments have shown that isolated ganglia will produce rhythmic bursting in motor nerves, similar to that seen in walking, after application of neurotransmitter substances or mechanical or electrical stimulation.

The pattern can also be extensively modified by sensory inputs that monitor the position and movement of the leg or the load the leg is bearing [8–10]. Sensory feedback can detect perturbations and help generate compensatory reactions by affecting the levels of motor firing. Some inputs can also change the time of the transitions between stance and swing.

Thus, each leg has its own ‘adaptable’ clock, but how are these timing mechanisms linked to produce coordinated locomotion? In the stick insect nervous system, as in most animals, intersegmental connections are made via interneurons [11]. To examine how these connections influence timing and coordination, Borgmann *et al.* [4] devised an elegant way to activate the pattern generators for the legs of one segment without affecting the pattern generators in other ganglia. A small dam was constructed surrounding an individual ganglion, creating a well in which pilocarpine (a muscarinic agonist) was applied (Figure 1A right). The connectives that form the neural circuits linking the ganglia remained intact. Helpfully, stick insects will walk after removal of all but one or two legs. With these preparations, it was possible to examine how one leg with normal sensory feedback affected the central oscillations of another leg. Figure 1B shows the result of applying pilocarpine to the mesothoracic (middle leg) ganglion after its peripheral nerves were cut, eliminating sensory feedback from the legs of that

segment. The transmitter agonist activated the pattern generators and produced slow reciprocal bursting in nerves to promotor and remotor muscles, similar to the patterns seen in walking. On the right of the figure, the ipsilateral front leg, which was left intact in this preparation, began stepping. During walking, bursting in the middle leg motor nerves continued but it became temporally linked to the movements of the front leg. Thus, the activation of the front leg pattern generator and its sensory feedback entrained the pattern generator of the middle leg; however, the timing of bursts was in phase (synchronous) rather than out of phase and alternating, as seen in intact animals.

Could local sensory inputs be responsible for establishing the appropriate phases of activation? To test this hypothesis, animals were studied in which one front leg was intact and the proximal segments of the ipsilateral middle leg were left attached to the body. This preparation allowed for mechanical stimulation of receptors in the middle leg (campaniform sensilla) that detect load [12]. Leg movements were elicited without any pharmacological activation. When the front leg began stepping (Figure 1C), in-phase bursting occurred in motor nerves of the middle legs as in the previous experiments. Stimulation of the load receptors of the middle leg was then initiated. This shifted the phase of bursting and entrained firing in the motor neurons of the middle leg so that the timing was dominated by the sensory inputs. When sensory stimulation was set at the correct times — similar to those in an intact animal — the resultant motor activity alternated in phase with the activity in the front leg. Thus, Borgmann *et al.* [4] had reconstructed the elements of timing to produce the appropriate coordination of leg movements.

The results of these experiments show that the neural control of coordination in walking is a balance of intersegmental effects and local control, with the effects of local feedback predominating. The intersegmental connections alone could strongly influence coordination and entrain the pattern generator in the adjacent ganglion (if it had no sensory inputs). This general activation could ensure that all the pattern generators are excited above threshold when

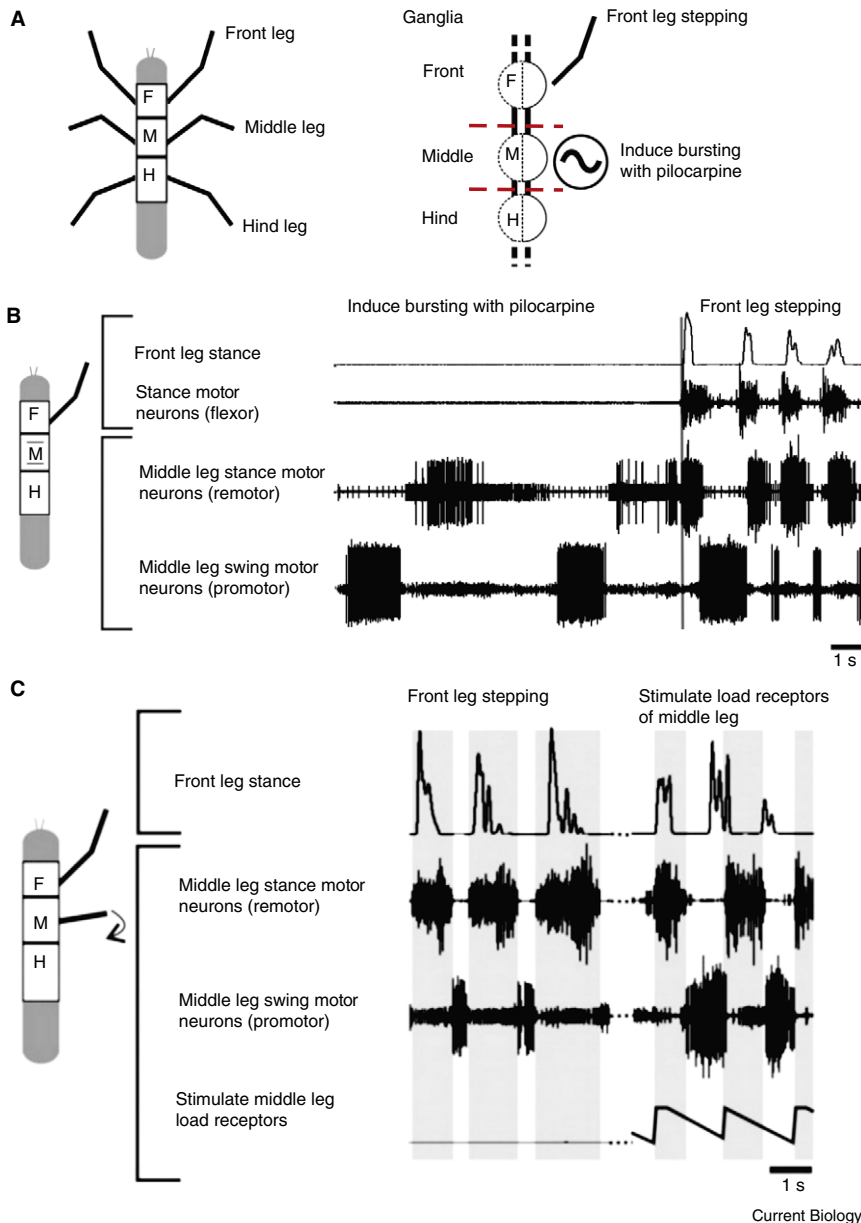


Figure 1. Neural control of leg coordination in stick insects.

(A) Stick insects have three pairs of legs, front (F), middle (M) and hind (H) legs. Walking movements are produced in each pair of legs by central pattern generators within the segmental ganglion. Stepping was elicited in animals in which all legs were removed except one front leg. Bursting in the pattern generators to the middle legs could be selectively induced by applying pilocarpine to its ganglion. (B) Pilocarpine induced slow rhythmic alternating bursting in the middle leg stance (remotor) and swing (promotor) motor neurons. When the front leg began stepping, bursting in the middle leg was entrained to movements of the front leg; however, the pattern of coordination was synchronous and not alternating as normally occurs in walking. (C) In this experiment, part of the middle leg was left intact to permit stimulation of receptors (campaniform sensilla) that detect load. In the absence of sensory stimulation (lowest trace) bursting in motor nerves in the middle leg (stance activity indicated by grey bars) was in phase with the front leg. Bursting shifted to the normal pattern of alternation during activation of load receptors at appropriate times. (The recordings in this figure are from [4].)

walking is initiated. The function of the in-phase coordination was not clear but similar timing has been seen in other experiments. For example, when

legs are autotomized in crustacea and the distal segments are lost, the stump of a leg moves in phase with the leg anterior to it [13].

However, signals from load receptors of the middle legs can override this entrainment and produce bursting in muscles at appropriate times. Sense organs that detect load have been shown to affect the timing of leg movements in experiments and simulations of walking in both vertebrates and invertebrates. Yang and colleagues [14,15] found that loading has strong effects on walking in humans, particularly in the initiation of the swing phase, which is delayed until a leg is unloaded. What determines the timing of firing of sensory inputs that detect loading and unloading? In normal walking, a leg is unloaded by its movement away from the center of mass and by the mechanical action of other legs. When some legs enter stance and assume load, the legs already in stance are unloaded, allowing them to enter into swing. If this process is repeated in time, coordinated locomotion will tend to be produced simply by mechanical properties and the effects of local sensory feedback.

In a simulation of cat walking, Ekeberg and Pearson [16] found that stable gaits could be established in the hind legs even without direct connections between pattern generating circuits provided that sensory signals of load were present. Giszter *et al.* [17] found that apparent coordination of movements of the front and hind legs of rats following spinal cord transection was probably achieved via local reflexes with some guidance through forces exerted by the trunk. The pattern of activity of load detecting sense organs, needed to establish the appropriate coordination in the experiments of Borgmann *et al.* [4], may therefore be due to leg mechanics and the effects of sensory feedback within single ganglia [18]. Further experiments are needed to test whether these mechanical effects and emergent properties make similar contributions to coordination in walking of stick insects.

Thus, the final pattern of leg movements occurs through a balance of neuronal mechanisms of intersegmental coordination, local feedback control, and, potentially, emergent properties dependent upon mechanics. Such a pluralistic solution to control may be advantageous in animal locomotion and allow for adaptable locomotion in the control of walking machines.

References

1. Hirai, K., Hirose, M., Haidawa, Y., and Takenaka, T. (1998). The development of honda humanoid robot. Proc. IEEE International Conf. on Robotics and Automation, pp. 1321–1326.
2. McGeer, T. (1992). Principles of walking and running. In *Advances in Comparative and Environmental Physiology 11: Mechanics of Animal Locomotion*, R. McN. Alexander, ed. (Berlin: Springer-Verlag), pp. 113–139.
3. Pearson, K.G. (2008). Role of sensory feedback in the control of stance duration in walking cats. *Brain Res. Rev.* 57, 222–227.
4. Borgmann, A., Hooper, S.L., and Büschges, A. (2009). Sensory feedback induced by front-leg stepping entrains the activity of central pattern generators in caudal segments of the stick insect walking system. *J. Neurosci.* 29, 2972–2983.
5. Cruse, H. (1990). What mechanisms coordinate leg movement in walking arthropods? *Trends Neurosci.* 13, 15–21.
6. Grillner, S. (2003). The motor infrastructure: from ion channels to neuronal networks. *Nat. Rev. Neurosci.* 4, 573–586.
7. Büschges, A. (2005). Sensory control and organization of neural networks mediating coordination of multisegmental organs for locomotion. *J. Neurophysiol.* 93, 1127–1135.
8. Duysens, J., Clarac, F., and Cruse, H. (2000). Load regulating mechanisms in gait and posture, comparative aspects. *Phys. Rev.* 80, 83–133.
9. Zill, S., Schmitz, J., and Büschges, A. (2004). Load sensing and control of posture and locomotion. *Arthropod Struct. Dev.* 33, 273–286.
10. Ekeberg, O., Blumel, M., and Büschges, A. (2004). Dynamic simulation of insect walking. *Arthropod Struct. Dev.* 33, 287–300.
11. Akay, T., McVea, D.A., Tachibana, A., and Pearson, K.G. (2006). Coordination of fore and hind leg stepping in cats on a transversely-split treadmill. *Exp. Brain Res.* 175, 211–222.
12. Schmitz, J. (1993). Load-compensating reactions in the proximal leg joints of stick insects during standing and walking. *J. Exp. Biol.* 183, 15–33.
13. Clarac, F., and Chasserat, C. (1979). Experimental modification of interlimb coordination during locomotion of a crustacean. *Neurosci. Lett.* 12, 271–276.
14. Lamb, T., and Yang, J.F. (2000). Could different directions of infant stepping be controlled by the same locomotor central pattern generator? *J. Neurophysiol.* 83, 2814–2824.
15. Pang, M.Y.C., and Yang, J.F. (2002). Sensory gating for the initiation of the swing phase in different directions of human infant stepping. *J. Neurosci.* 22, 5734–5740.
16. Ekeberg, O., and Pearson, K. (2005). Computer simulation of stepping the hind legs of the cat: an examination of mechanisms regulating the stance-to-swing transition. *J. Neurophysiol.* 94, 4256–4268.
17. Giszter, S.F., Davies, M.R., and Graziani, V. (2008). Coordination strategies for limb forces during weight-bearing locomotion in normal rats, and in rats spinalized as neonates. *Exp. Brain Res.* 190, 53–69.
18. Zill, S.N., Keller, B.R., and Duke, E.R. (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.* doi: 10.1152/jn.00056.2009, online.

Department of Anatomy and Pathology,
Joan C. Edwards School of Medicine,
Marshall University, Huntington,
WV 25704, USA.
E-mail: sensillum@aol.com

DOI: 10.1016/j.cub.2009.03.044

Multisensory Integration: Frequency Tuning of Audio-Tactile Integration

Multisensory information can be crucial, yet in many circumstances we have little, if any, awareness of the effects of multisensory inputs on what appear to be entirely unisensory perceptions. A recent study shows robust effects of auditory input on tactile frequency discriminations and that this auditory cross-sensory interference has specific tuning.

John J. Foxe

Gentlemen, have you tried shaving with your ears plugged? Of course you haven't and perhaps this doesn't even strike you as all that difficult an undertaking, not like being asked to do it without a mirror. And goodness knows what it would be like to shave if you were asked to apply topical anesthetic to your face beforehand. Still, the next time you shave, take a little extra time to consider the sensory signals that you rely on during this tedious job. I bring up shaving here because it has often struck me just how much one relies on the combination of auditory and somatosensory inputs during this routine chore. It is a truly multisensory task and the interplay of the sound of the razor passing over unshaven areas and the feel of the blades on the skin is an excellent demonstration of the interplay of these two sensory systems during a very personal tactile roughness task. I'm not so sure that the effect is quite as strong for the opposite sex when shaving

more distal and less innervated aspects of the body, but I'll assume there are reasonable parallels.

One of the earliest formal demonstrations of the role of auditory inputs on tactile sensations was also one of the most extraordinary, and is not unrelated to my shaving example. Jousmaki and Hari [1], writing in *Current Biology*, showed that by artificially altering the rubbing sounds that participants heard when asked to rub their palms together, one could dramatically alter the tactile sensations that subjects reported. They used a simple setup where they placed a microphone next to the hands and then played the rubbing sounds the hands made back through a pair of headphones. In some cases, the sounds were unaltered and in others, all frequencies above 2000 Hz were either enhanced or dampened by 15 decibels. Participants were asked to rate their tactile sensation on a scale between relative moistness (roughness) and dryness (smoothness). Two effects were seen.

First, the louder the rubbing sounds were, the smoother and dryer the rubbing experience became. So, it became clear that auditory inputs could affect tactile roughness judgments. More importantly for our purposes here, they also found that by enhancing the high-frequency component (2 kHz) of the rubbing sound, the majority of their subjects also experienced a significant shift in the perceived smoothness/dryness of the skin surface. A number of the subjects spontaneously reported the rather extraordinary sensation of having a leaf of parchment paper interposed between their rubbing hands and so the effect has entered the vernacular in the multisensory field as the 'parchment-skin illusion'.

This study firmly established the role of auditory inputs as an important adjunct to tactile judgments of texture, but it also hinted that there might be a tuning function underlying this effect, as it was because of the manipulation of the high-versus-low frequency ratios of the auditory inputs that those tactile perceptions were altered. Guest *et al.* [2] corroborated this effect some years later. Participants in their study made forced-choice discriminations regarding the roughness of abrasive surfaces, and their data showed that roughness perception was modulated by the frequency content of the auditory feedback, with attenuation of high frequency inputs causing a shift in perception towards greater smoothness.