Patterns of Locomotor Drive to Motoneurons and Last-Order Interneurons: Clues to the Structure of the CPG

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Burke, R. E., A. M. Degtyarenko, and E. S. Simon. Patterns of locomotor drive to motoneurons and last-order interneurons: clues to the structure of the CPG. J Neurophysiol 86: 447–462, 2001. We have examined the linkage between patterns of activity in several hindlimb motor pools and the modulation of oligosynaptic cutaneous reflex pathways during fictive locomotion in decerebrate unanesthetized cats to assess the notion that such linkages can shed light on the structure of the central pattern generator (CPG) for locomotion. We have concentrated attention on the cutaneous reflex pathways that project to the flexor digitorum longus (FDL) motor pool because of that muscle’s unique variable behavior during normal and fictive locomotion in the cat. Differential locomotor control of last-order excitatory interneurons in pathways from low-threshold cutaneous afferents in the superficial peroneal and medial plantar afferents to FDL motoneurons is fully documented for the first time. The qualitative patterns of differential control are shown to remain the same whether the FDL muscle is active in early flexion, as usually found, or during the extension phase of fictive locomotion, which is less common during fictive stepping. The patterns of motor pool activity and of reflex pathway modulation indicate that the flexion phase of fictive locomotion has distinct early versus late components. Observations during “normal” and unusual patterns of fictive stepping suggest that some aspects of locomotor pattern formation can be separated from rhythm generation, implying that these two CPG functions may be embodied, at least in part, in distinct neural organizations. The results are discussed in relation to a provisional circuit diagram that could explain the experimental findings.

Introduction

There is abundant evidence that the spinal cord of vertebrates, from primitive fish to carnivores, contains an autonomous central pattern generator (CPG) that can produce coordinated patterns of motoneuron activation that resemble those observed in actual locomotion (Grillner 1981; Rossignol 1996). A CPG for locomotion may also exist in the human spinal cord, although it is more difficult to demonstrate than in quadrupedal mammals (Calancie et al. 1994; Dimitrijevic et al. 1998). The hallmark for identification of a CPG within the CNS is the production of recognizable and reproducible patterns of rhythmic output in the absence of instructive external drive from other parts of the CNS or from peripheral sensory feedback.

Traditionally, the CPG for locomotion has been studied in terms of rhythmic drive to motoneurons. However, it has been known for some time that a variety of reflexes are modulated in amplitude and even reversed in sign during different phases of the stepping cycle, both in animals (Abraham et al. 1985; Andersson et al. 1978; Buford and Smith 1993; Duyvens and Pearson 1976; Forssberg 1979; Forssberg et al. 1975, 1977) and man (Duyvens et al. 1990; Stein and Capaday 1988; Van Wezel et al. 1997). Intracellular recordings from motoneurons during fictive locomotion have provided clear evidence that the locomotor CPG exerts powerful control of transmission through reflex pathways as assessed by phasic modulation of synaptic potentials (Andersson et al. 1978; Schomburg and Behrends 1978a,b).

In a series of papers from this laboratory (Degtyarenko et al. 1996, 1998a,b; Fleshman et al. 1984; Floeter et al. 1993; Gossard et al. 1996; Moschovakis et al. 1991; Schmidt et al. 1988), the control of cutaneous and muscle afferent reflex pathways during fictive locomotion was used as a tool to investigate the organization of spinal last-order interneurons that project to particular motor nuclei (reviewed in Burke 1999). This work concentrated on synaptic pathways that project to the flexor digitorum longus (FDL) muscle because its motoneurons exhibit unique patterns of activity during locomotion in normal cats (Carlson-Kuhta et al. 1998; O’Donovan et al. 1982; Smith et al. 1998; Trank and Smith 1996). During unperturbed stepping, the FDL usually exhibits little or no activity during the stance phase but fires a brief, vigorous burst around the time of foot lift-off. This is quite different from the activity in FDL’s close, albeit not exact, mechanical synergist flexor hallucis longus (FHL) (see Lawrence et al. 1993; Young et al. 1993), which is active throughout the stance phase of stepping and becomes silent just before FDL bursts. The difference is particularly interesting because FDL and FHL share mutual monosynaptic group Ia excitation (Fleshman et al. 1984), which is usually an indication of functional synergy (Eccles et al. 1957; Lloyd 1960). The distinction between FDL and FHL firing patterns persists during backward walking in the cat, although in this case, FDL fires at the transition into stance rather than into swing (Trank and Smith 1996).

The present paper examines observations obtained largely from FDL motoneurons during spontaneous and stimulation-evoked fictive locomotion with regard to what they suggest...
about the organization of the locomotor CPG itself. A preliminary report has appeared in abstract form (Burke et al. 1996).

**Methods**

The methods used for the present experiments have been described in recent reports from this laboratory (Degtyarenko et al. 1996, 1998a,b; Gossard et al. 1996; Moschovakis et al. 1991). Some of the results reported in the present paper were extracted from data tapes made during this earlier work but not previously published. We are grateful to Drs. Adonis Moschovakis, Gerald N. Sholomenko, Mary Kay Floeter, and Jean-Pierre Gossard for their participation in collecting these data. The experiments were conducted in accordance with the “Principles of Laboratory Animal Care” (National Institutes of Health Publication 86-23) and were approved by the National Institute of Neurological Disorders and Stroke Committee on Animal Care and Use.

Briefly, 50 adult female cats (2.5–4.0 kg) were used. Halothane anesthesia was induced by mask and maintained (1–2% in air or oxygen) via a tracheal cannula during surgery. One common carotid artery was cannulated for blood pressure monitoring and the other was ligated. Intravenous catheters were placed in both cephalic veins for administration of norepinephrine and fluids as necessary to maintain blood pressure within physiological limits. The urinary bladder was catheterized. Rectal temperature was maintained near 38°C with a heating pad and lamp.

The following muscle nerves in the left hindlimb were cut and mounted on bipolar platinum wire electrodes for stimulation and recording: posterior biceps-semitendinosus (PBST), lateral gastrocnemius and soleus (LGS), medial gastrocnemius (MG), FDL, FHL, tibialis anterior (TA), and extensor digitorum longus (EDL). Cutaneous branches of the superficial peroneal (SP), medial plantar (MPL), and, in a few experiments, the saphenous (SAPH) nerves were freed but not cut; all were mounted on bipolar stimulating electrodes. Muscle nerves in the other limbs were not prepared for recording because the primary aim of these experiments was to examine ipsilateral reflex pathway modulation.

After a laminectomy exposing spinal segments L₄–S₁, the animals were transferred to a stereotaxic frame and skin flaps surrounding the spinal cord, and the hindlimb nerves were used to construct paraffin oil pools. Precollicular postmammillary decerebration was performed by removing all rostral brain tissue and catarzulized vessels. Anesthesia was then discontinued. The animal was paralyzed with gallamine triethiodide (Flaxedil; 10 mg/kg supplemented every 40–60 min) and, in a few experiments, the saphenous (SAPH) nerves were freed but not cut; all were mounted on bipolar stimulating electrodes. Muscle nerves in the other limbs were not prepared for recording because the primary aim of these experiments was to examine ipsilateral reflex pathway modulation.

Recording and stimulation

The cord dorsum potential (CDP) was recorded with a platinum ball electrode placed near the dorsal root entry zone at the L₄–L₇ border. Stimulation intensity to peripheral nerves was expressed in multiples of the threshold for the most excitable fibers in the nerve (usually at Stimulation intensity to peripheral nerves was expressed in multiples of the threshold for the most excitable fibers in the nerve (usually at 1). Intracellular recordings from motoneurons in the L₄–L₇ segments were made with glass micropipettes (1.0–2.0 μm tip diameter) filled with 2 M K⁺ acetate solution containing 26 mM QX314 (Alomone Laboratories, Jerusalem, Israel) to suppress sodium-dependent action potentials (Frazier et al. 1970). Motoneurons were identified by antidromic invasion from muscle nerve stimulation during the several minute period required for spike blockade to occur.

To produce fictive locomotion, a monopolary tungsten electrode insulated except at the tip was placed into the mesencephalic locomotor region (MLR; nominal coordinates: P2, L4, HC = −1), usually ipsilateral to the side of recording. Constant-current (70–150 μA) biphasic, charge balanced pulses (pulse duration, 0.2–0.5 ms separated by an equal interval) were delivered in trains (12–30 Hz), referenced to a wire in the neck muscles. The optimal position of the MLR electrode was adjusted to produce rhythmic alternating activity in hindlimb muscle nerves (fictive locomotion), which was usually accompanied by distinctive CDP waves (Degtyarenko et al. 1998a).

Data collection and analysis

Intracellular potential, CDP, and electroneurogram (ENG) activity in muscle nerves (usually LGS, FHL, FDL, TA or EDL, and PBST), were recorded with an eight-channel digital videotape recorder (Instrutech VR-100B; band-pass DC-9 kHz for the intracellular channel). Timing pulses that were synchronized with stimuli delivered to peripheral nerves and to the MLR were recorded on digital signal channels to permit selected synaptic potentials to be averaged during off-line data analysis.

Synaptic potentials were evoked in motoneurons during fictive locomotion by alternately stimulating the SP and MPL nerves, usually at a rate of 10 Hz each (Fig. 1) (see Moschovakis et al. 1991 for detailed discussion of the technique). The data from selected portions of the data tapes were digitized off-line (10 kHz) using an Apple Macintosh PowerPC computer and National Instruments NB-MIO-16 A/D board. Data collection and analysis were done with "virtual instrument" programs written with the LabView software package (National Instruments, Austin, TX). In most cases, the phases of fictive locomotion were defined from the digitized ENG data streams, which were rectified and smoothed using decremental look-ahead

![Figure 1](http://jn.physiology.org/DownloadedFrom)
exponential weighting with a time constant of ~34 ms. This algorithm provided a good match between the onsets and offsets of raw ENG bursts and the smoothed waveforms.

The program allowed ENG burst onsets and offsets to be determined either automatically by threshold crossing or manually when signal-to-noise ratios were low. The start of each flexion phase during fictive locomotion was taken as the onset of firing in the flexor motoneurons, FDL and/or PBST, and the offset of firing in extensor nerves (LGS and/or FHL) and ended with the termination of bursts in TA or EDL muscle nerves and the onset of extensor firing. The remaining time periods were defined as extension phases (e.g., Fig. 3). The flexion and extension phases were each subdivided into three equal time bins. Because of their variable durations, the time bins in the two phases usually did not have the same absolute durations.

The timing pulses associated with central and peripheral nerve stimuli were used to trigger the computer to average together the intracellular potentials and CDPs resulting from stimuli falling into the appropriate locomotion phase bins (Degtyarenko et al. 1996; Moschovakis et al. 1991). Each average included at least eight sweeps and sweep numbers were usually >20. The MLR stimuli were not synchronized to these pulses. When MLR stimulation produced significant postsynaptic potentials (PSPs), cutaneous PSPs were averaged only when they fell within an acceptance window that excluded nearby MLR stimuli. The analysis program also allowed exclusion of responses that produced action potentials (Degtyarenko et al. 1996).

Central EPSP latencies were measured as the time between the peak of the first deflection of the CDP and the onset of the intracellular PSP (e.g., Fig. 4, B and D). This assumes that the excitatory PSP (EPSP) results from action of the most rapidly conducting afferents in the peripheral nerve.

RESULTS

The aim of the present report is to discuss the implications of interactions between cutaneous and muscle afferent reflex pathways and the CPG for locomotion in the adult cat spinal cord. Some of the material in this paper is drawn from experiments that have been reported elsewhere in other contexts (Degtyarenko et al. 1996, 1998a,b; Gossard et al. 1996). However, the specific observations in this paper have not been published previously.

Locomotor modulation of cutaneous EPSP in FDL motoneurons

Previous publications from this laboratory have demonstrated differential modulation of oligosynaptic EPSPs produced by low-threshold afferents in the SP and MPL nerves in FDL motoneurons during fictive locomotion in adult cats (Moschovakis et al. 1991; see also Degtyarenko et al. 1996, 1998b). However, the earlier papers did not provide complete documentation of the available material. Figure 1 presents summary records of averaged SP EPSPs from 33 FDL motoneurons during extension and early flexion phases of fictive locomotion (B and C), and EPSPs during periods without fictive stepping in 12 of these cells (A). Corresponding records of MPL EPSPs in 32 of the same FDL cells are shown in D–F. With both inputs, EPSPs during extension phases resembled those at rest. However, the SP EPSPs during early flexion (Fig. 1C) were notably larger and displayed shorter central latencies. In marked contrast, the MPL EPSPs during early flexion were markedly reduced (Fig. 1F).

The amplitudes and latencies of these EPSPs are shown in Fig. 2. The data in each graph are indexed sequentially on the abscissae by increasing extension phase EPSP amplitudes (A and C, O; measured at 2.5-ms central latency, - - - in Fig. 1) or minimum central latencies (B and D; see METHODS). The amplitudes of SP and MPL EPSPs in the absence of fictive locomotion (“rest”) were roughly the same as those found during the extension phases of locomotion. However, the peak amplitudes of SP EPSPs at 2.5 ms during the flexion phase were considerably larger in most (25/33) FDL cells (Fig. 2A). In contrast, the flexion phase MPL EPSPs were either undetectable or much smaller than the extension phase responses in all 28 FDL cells that exhibited any extensor phase EPSP. Central latencies of SP EPSPs (Fig. 2B) were shorter during flexion than in extension or at rest in most cells (28/33), with the majority ≤2.0 ms (27/33). Over half of the sample of MPL EPSPs had central latencies ≤2.0 ms at rest or during the extension phase, and all but two FDL cells had MPL EPSPs with latencies ≤2.2 ms. It was not possible to measure central latencies of MPL EPSPs during flexion. Cutaneous EPSPs with central latencies ≤2.2 ms are assumed to be disynaptic in the subsequent material (see DISCUSSION).

Influence of afferent stimulation on FDL firing patterns

To define patterns of locomotor modulation of a reflex pathway it is necessary to superimpose low-frequency repetitive stimulation of pathway afferents during spontaneous or MLR-induced fictive locomotion (Schmidt et al. 1988; Schomburg and Behrends 1978b). Superimposing afferent input on locomotor rhythms can change step-cycle durations as well as patterns of motoneuron activity, especially with relatively high-frequency input (Fleschman et al. 1984). Although we have not systematically analyzed the possible alterations in the baseline “state” of the locomotor CPG produced by our method of probing reflex pathways, considerable experience with this method suggests that low-frequency, low-strength cutaneous stimulation produces only subtle changes in the system. Indeed, such changes are a major issue in this report.

In the example shown in Fig. 3A, with stimulation of the SP nerve alone at 10 Hz superimposed on spontaneous locomotion, FDL fired in short bursts during the first third of the flexion phase, accompanied by sharp depolarizing locomotor drive potentials (LDPs) (Jordan 1983) evident in the intracellular record from an FDL motoneuron (top trace; arrows). In contrast, during superimposed 10-Hz stimulation of the MPL nerve alone, the depolarizing LDPs and the FDL bursts disappeared (open arrows), without changing the basic locomotor rhythm. Mean step cycle durations were 2.5 ± 0.3 (SD) s during SP alone and 2.4 ± 0.6 s during MPL alone stimulation. The hyperpolarizations of the FDL motoneuron during the last 2/3 of flexion in the two episodes were superimposable. Comparison of averaged hyperpolarizing pulses delivered to the motoneuron (5 nA, 10 Hz interleaved with nerve stimuli; downward deflections in the intracellular traces) showed that the cell input resistance (\(R_N\)) decreased during late flexion (\(R_N = 0.60 \text{ M\Omega} \) from \(R_N = 0.75 \text{ M\Omega} \) during extension), indicating that the hyperpolarization resulted from active inhibition of the FDL motoneurons coincident with TA motor pool firing. Similar behavior was observed in several other animals.

An analogous result was found in a different animal with SP stimulation at two intensities superimposed on spontaneous fictive stepping (Fig. 4). With 10 Hz SP stimulation at 1.5 \(\times\),
there were no depolarizing LDPs in the intracellular records from an FDL motoneuron, and no early flexion bursts in either FDL or PBST muscle nerves (open arrows). Nevertheless, the averaged SP EPSPs were clearly modulated, with maximum facilitation during F1 (Fig. 4B, heavy arrow) and minimum central latency of 2.2 ms. Increasing the stimulus strength to 2.0 × T produced depolarizing LDPs and bursting in both FDL and PBST nerves (Fig. 4C), with little evident alteration in the frequency of fictive stepping (the time base in A and C is the same). The EPSPs averaged with the higher stimulus intensity were larger and the minimum central latency decreased, by ~0.4 ms, to 1.8 ms (Fig. 4D; arrows). The same qualitative pattern of facilitation was evident at both SP stimulus intensities. The similarities in SP EPSP shapes and modulation suggest that the short-latency responses at 1.5 × T (~2.2 ms) were probably disynaptic (see DISCUSSION).

**Extensor phase activity in FDL**

In addition to its stereotypical activation at the transition from stance to swing during walking in intact cats (O’Donovan et al. 1982; Trank and Smith 1996), FDL motoneurons can also exhibit variable amounts of activity during the stance phase (i.e., co-active with FHL) during perturbed step cycles and in some other situations (O’Donovan et al. 1982). Extensor phase FDL activity can also occur during fictive locomotion (Flesham et al. 1984; Moschovakis et al. 1991), although we have been unable to find any set of conditions that produce it reliably. Nevertheless, some cases of stable fictive stepping were encountered during which FDL was co-activated with FHL during the extension phase during intracellular recording from FDL motoneurons and stimulation of cutaneous afferents, allowing us to evaluate the modulation of SP and MPL EPSPs in this state.

In the example shown in Fig. 5, during MLR-evoked fictive stepping with alternating SP and MPL stimulation (2 × T for each nerve) superimposed, the FDL ENG was co-active with LGS and FHL firing, without F1 bursts in the ENG (open arrows). The intracellular potential (FDL IC) showed only hyperpolarizing LDPs during F2 and F3, without F1 depolarizations (open arrows). However, Fig. 5B shows that the pattern of SP EPSP modulation was essentially the same as observed during bouts of fictive locomotion when FDL was active in F1 (cf. Fig. 4D). Unfortunately, the MPL nerve generated only small inhibitory PSPs (IPSPs) in this motoneuron during all phases of locomotion (not illustrated).

The example in Fig. 6 illustrates a case in which the usual patterns of F1 FDL firing, depolarizing LDPs, and differential modulation of SP and MPL EPSPs were all present during relatively slow, spontaneous fictive locomotion (Fig. 6, A and B). However, when the MLR was stimulated, the...
stepping rate increased markedly and FDL was co-active with FHL during the extension phase. The F1 depolarization and FDL ENG bursts disappeared (Fig. 6C, open arrows). However, the pattern of modulation of SP and MPL EPSPs (D) were qualitatively similar to that in B, although there was less SP EPSP enhancement and less complete suppression of late MPL EPSPs during F2 and F3 than during spontaneous locomotion.

**Two distinct subphases during the flexion phase**

The postsynaptic drive from the locomotor CPG to FDL motoneurons changes dramatically from excitation to inhibition about one-third of the way through the flexion phase in many examples of fictive stepping (e.g., Figs. 3A and 4C). Although the FDL motor pool can fire in F1 or during extension (and occasionally in both), we have never observed FDL firing during mid- and late flexion during fictive locomotion. The facilitation of disynaptic SP EPSPs during F1 usually disappears in F2 and F3 (Figs. 4, B and D, and 9B) (see also Degtyarenko et al. 1996, their Fig. 9; Moschovakis et al. 1991, their Figs. 4 and 9), accompanied by progressive diminution of the longer latency, trisynaptic EPSPs (Figs. 4–6). These observations suggest the existence of distinct subphases in “early” versus “late” flexion. We encountered one unusual animal that provided additional evidence for these subphases.

The preparation illustrated in Fig. 7 exhibited spontaneous fictive locomotion with irregular step cycles during alternating stimulation of SP and MPL nerves at 10 Hz. The durations of FHL (extensor) phase bursts varied between cycles while the durations of EDL (mid- to late flexor) were uniformly brief. However, the most striking observation was that FDL bursts, in conjunction with PBST, were alternately long and short, without the brief F1 bursts characteristic of most examples of fictive locomotion (e.g., Figs. 4C and 6A). Remarkably, each of the flexor phases ended with uniformly short-duration bursts in EDL. There was no overlap between FDL bursts and firing in EDL (Fig. 7B). The simultaneous intracellular record from an FDL motoneuron (FDL IC) showed depolarizing LDPs during FDL firing with little evident hyperpolarization during EDL bursts. In fact, the membrane potential was most hyperpolarized during FHL activity.

Figure 7, C and D, respectively, illustrate modulation of SP and MPL EPSPs in the FDL motoneuron, averaged separately during three periods of ENG activity: FDL, EDL, and FHL. The SP EPSPs (C) were markedly enhanced during the periods when FDL motoneurons were active (F(FDL)) but returned to the extensor phase amplitude during the uniformly short bursts of EDL activity (F(EDL)). The MPL EPSPs exhibited the usual flexion phase suppression during EDL activity. However, during the F(FDL) phase, the initial EPSP component appeared unchanged from extension, but, surprisingly, there was enhancement of a later, clearly trisynaptic component (C, arrow). Although the minimum central latencies of both SP and MPL EPSPs were both slightly longer than 2.0 ms, we assume that they were both disynaptic while the later components (C and D, heavy arrows) were trisynaptic (see DISCUSSION). We have previously observed facilitation of trisynaptic MPL EPSPs during FDL firing in unusual instances of extensor phase FDL activity (Moschovakis et al. 1991, their Figs. 9 and 10).

Stimulation of the SP nerve generates disynaptic IPSPs in EDL motoneurons during early flexion in fictive locomotion (Degtyarenko et al. 1996). Intracellular records from an EDL motoneuron that exhibited this behavior in the same cat illustrated in Fig. 7 are shown in Fig. 8. The SP IPSPs in this EDL motoneuron were enhanced through the entire period of flexion (Degtyarenko et al. 1996, their Fig. 4). The disynaptic MPL EPSP in this cell, which was not shown in that paper, had a central latency of 1.8 ms. Quite unlike the MPL response in the FDL motoneuron (Fig. 7D), the MPL EPSP in the EDL cell (Fig. 8) showed complete suppression during the FDL as well as EDL firing periods, with no facilitation of the trisynaptic component (cf. Fig. 7D).

**Evidence for independent cycling of extensor and flexor CPG centers**

Figure 9A illustrates another unusual example of fictive locomotion in which the activity in the extensor LGS exhibited sinusoidal waxing and waning activity with ~3 s between...
cycles. Uniformly short bursts of FDL, TA, and PBST firing with the normal flexion phase sequencing were interjected into this rhythm, skipping extensor cycles at the start of the recording and later locked to the first half of the extensor cycles. These flexion bursts were accompanied by early (F1) depolarizing LDPs and later hyperpolarization in the FDL intracellular record (A, FDL IC; 3). In contrast to the rather bizarre and variable flexion bursts shown in Fig. 7A, the flexion bursts in this example gave the appearance of stereotyped events that were triggered in variable phase relations with the extensor rhythm.

Averaged records of SP (B) and MPL EPSPs (C) were obtained during the F1–F3 phases of flexion and during periods when LGS activity was high versus low (Ext on and Ext off, respectively). The SP EPSPs exhibited the usual facilitation of disynaptic (B, —→) and trisynaptic components during F1 with diminishing enhancement later in flexion. All of these responses were larger than those during the extension phase, which showed only a small difference depending on whether the LGS motor pool was active or not. Suppression of MPL EPSPs was evident throughout flexion, but there may have been some extensor phase facilitation of the trisynaptic component between LGS waves. Analogous observations of apparent independent cycling of extensor muscles with variable coupling to flexor bursts were made in two other cats.

Apparent independent cycling of flexor muscle pools is illustrated in Fig. 10, obtained during MLR-evoked fictive stepping during intracellular recording from an LGS motoneuron (A, LGS IC) during interleaved stimulation of the SP nerve at 2.0 × T and 10 Hz (see METHODS) was also superimposed. Flexion phase suppression of the MPL EPSPs (not shown, see Figs. 1 and 2) was found at both intensities of SP stimulation.

FIG. 4. Stimulation of SP nerve alone at 2 intensities can change phase-related depolarizing FDL drive but not SP EPSP modulation during spontaneous fictive locomotion. A: stimulation of SP at low strength (1.5 × T; 10 Hz) resulted in flexion phase hyperpolarization in an FDL motoneuron (FDL IC) without early flexion depolarizing LDPs or FDL [or posterior biceps-semimendinosus (PBST)] bursts (open arrows). B: SP EPSPs sorted and separately averaged during six phases of the step cycles shown partly in A (F1, F2, F3 averaged during the early, middle, and late thirds of flexion, respectively and similarly for the extension phases, E1, E2, and E3; see METHODS). Despite the absence of detectable excitatory flexion phase drive to FDL motoneurons, oligosynaptic SP EPSP were nevertheless facilitated during F1 (heavy arrow), with slight facilitation of trisynaptic components in F2 and F3. Note that the minimum central latency was −2.2 ms for the first component, while the later, presumably trisynaptic component latency was −3 ms (thin dashed arrow). The depolarization that started at −1.0 ms central latency was an extracellular field potential (ECF). C: increasing SP stimulation intensity to 2.0 × T produced the usual F1 phase depolarizations in the FDL motoneuron and bursts of ENG activity in both FDL and PBST nerves (filled arrows). D: with the higher strength SP stimulation, the pattern of SP EPSP facilitation was the same as in B, but the responses were larger and the minimum central latency shortened to −1.8 ms. The latency of the second, presumably trisynaptic component (thick gray arrow) also shortened a comparable amount (thin dashed arrow). During this episode of locomotion, interleaved stimulation of the MPL nerve at 2.0 × T and 10 Hz (see METHODS) was also superimposed. Flexion phase suppression of the MPL EPSPs (not shown, see Figs. 1 and 2) was found at both intensities of SP stimulation.
EDL activity increases toward the end of flexion (e.g., Fig. 6), often in concert with FDL (e.g., Figs. 3–6), and then wanes as PBST begins to fire at the onset of the flexion phase, which phase difference fits with other examples of fictive stepping in that were about 180° out of phase with those in EDL. This trained. The PBST neurogram also showed waves of activity interneurons that inhibit LGS during flexion were also en- were time-locked to the EDL waves, suggesting that inhibitory interneurons that inhibit LGS during flexion were also en- trained. The PBST neurogram also showed waves of activity that were about 180° out of phase with those in EDL. This phase difference fits with other examples of fictive stepping in which PBST begins to fire at the onset of the flexion phase, often in concert with FDL (e.g., Figs. 3–6), and then wanes as EDL activity increases toward the end of flexion (e.g., Fig. 6A). The short extensor bursts in the LGS and FHL nerves appeared to be time-locked to the sinusoidal cycling of EDL but with variable numbers of EDL cycles between them. Each extensor burst began in the middle of the next expected wave of EDL firing, preceded by rapid, synchronized EDL bursts that were time locked to the MLR stimulation at ~14 Hz. As in Fig. 9, these interjected extensor bursts did not appear to change the EDL rhythm.

Figure 10, B and C, illustrates averaged SP and MLF EPSPs, respectively. Apparently di- and trisynaptic SP EPSPs were generated in the LG motoneuron only when the LGS nerve was silent, irrespective of whether EDL was active or not. They were completely absent during the interjected extensor bursts (B, Ext). We have observed similar modulation of oligosynap- tic SP EPSPs in a minority of triceps surae motoneurons (unpublished results). Low-frequency stimulation of the MLR produces mono- and disynaptic EPSPs in many types of hind-limb motoneurons. The disynaptic component exhibits systematic enhancement during the stepping phase when the motoneu- rons are active (Floeter et al. 1993; Gossard et al. 1996). Figure 10C illustrates this extensor phase facilitation of disynaptic MLF EPSPs during the interjected bursts of LGS and FHL activity. The disynaptic MLF EPSPs were unchanged during the flexor cycling.

DISCUSSION

The observations in this paper support the early surmise (Burke and Fleshman 1986) that the patterns of modulation of reflex pathways can provide useful clues to the structure of the CPG for locomotion because they are as robust markers for phase-related activity as are the activity patterns in different motor pools. We have focused primarily on the FDL muscle because of its unique behaviors during normal and fictive locomotion. In the relatively few studies available in which FDL EMG activity in intact cats has been studied in isolation (Abraham et al. 1985; Carlson-Kuhta et al. 1998; Loeb 1993; O’Donovan et al. 1982; Trank and Smith 1996), FDL is normally activated in a brief burst at the transition from late stance to early swing, entirely out of phase with its mechanical synergist FHL. Activities of the two muscles are also mostly out of phase during actual (Carlson-Kuhta and Smith 1990; O’Donovan et al. 1982) and fictive scratching (Degtyarenko et al. 1996). Remarkably, this behavior of the FDL motoneuron pool persists long after it cross-reinnervates the soleus muscle (O’Donovan et al. 1985). However, the FDL can also exhibit varying amounts of activity during the stance phase and co-activation with FHL during irregular stepping and in other actions in intact cats (O’Donovan et al. 1982), as well as during fictive locomotion (Figs. 5 and 6) (Fleshman et al. 1984; Moschovakis et al. 1991).

The fact that these distinctive behaviors are found during fictive locomotion in spinalized as well as decerebrate prepara- tions (Moschovakis et al. 1991; Schmidt et al. 1988) suggests that the underlying circuits are represented in the spinal CPG for locomotion. The present material provides evidence about the modulation of cutaneous reflex pathways during these different FDL activity states. The data are used to develop a suggested circuit diagram that speaks to the organization of the CPG as it operates during fictive locomotion. In the relatively few studies available in which the patterns of modulation of cutaneous reflex pathways can provide useful clues to the structure of the CPG for locomotion because they are as robust markers for phase-related activity as are the activity patterns in different motor pools. We have focused primarily on the FDL muscle because of its unique behaviors during normal and fictive locomotion. In the relatively few studies available in which FDL EMG activity in intact cats has been studied in isolation (Abraham et al. 1985; Carlson-Kuhta et al. 1998; Loeb 1993; O’Donovan et al. 1982; Trank and Smith 1996), FDL is normally activated in a brief burst at the transition from late stance to early swing, entirely out of phase with its mechanical synergist FHL. Activities of the two muscles are also mostly out of phase during actual (Carlson-Kuhta and Smith 1990; O’Donovan et al. 1982) and fictive scratching (Degtyarenko et al. 1996). Remarkably, this behavior of the FDL motoneuron pool persists long after it cross-reinnervates the soleus muscle (O’Donovan et al. 1985). However, the FDL can also exhibit varying amounts of activity during the stance phase and co-activation with FHL during irregular stepping and in other actions in intact cats (O’Donovan et al. 1982), as well as during fictive locomotion (Figs. 5 and 6) (Fleshman et al. 1984; Moschovakis et al. 1991).

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Reflex pathway length

Conclusions that can be drawn from reflex pathway modulation during fictive locomotion are most secure when the pathway between peripheral afferents and the target motoneurons is disynaptic (i.e., when there is single layer of interposed interneurons) (see Lundberg 1975). Evidence discussed elsewhere (Degtyarenko et al. 1996, 1998b; Moschovakis et al. 1991) suggests that central latencies ≤2.0 ms indicate disynaptic connectivity in cutaneous reflex pathways but that under some conditions EPSPs with latencies ≤2.2 ms can be disynaptic, as found for disynaptic group I EPSPs that are clearly disynaptic (Degtyarenko et al. 1998b; their Fig. 7).

The central latencies for the sample of SP EPSPs in Fig. 2B ranged smoothly from 1.7 to almost 3 ms during the extension phase of fictive locomotion and at rest (1.9–2.6 ms). However, during F1 facilitation, the latencies in 27/33 FDL motoneurons were ≤2.0 ms and ≤2.3 ms in all but one cell. Central latencies for MPL EPSPs during the extension phase (Fig. 2D) increased smoothly from 1.6 to ~2.2 ms, with two examples ≥2.5 ms. The records of SP EPSPs in Fig. 4, B and D, show that simply increasing SP stimulus intensity decreased central latencies of both early and later EPSP components by ~0.4 ms, from a minimum of 2.2–1.8 ms. The latter is clearly disynaptic and it can be argued from the qualitative similarity of EPSP shapes at the two intensities that the early response at 1.3 T was in fact disynaptic, and the later one trisynaptic. For these reasons, we regard central latencies ≤2.2 ms as indicative of disynaptic connectivity for the SP and MPL pathways discussed in this paper (e.g., including SP EPSPs in Figs. 4 and 7).

Locomotor CPG is an embedded system

Central pattern generators are sometimes depicted as autonomous neural circuits, partly perhaps because the best known
examples in invertebrates can indeed function when completely isolated from the rest of the organism’s nervous system (e.g., Selverston et al. 1998). However, even invertebrate CPGs in situ receive information and may deliver feedback to the CNS in which they are embedded (Selverston 1980). Operation of a CPG can continue in the absence of sensory input but it is clear that sensory information modifies and controls many aspects of CPG output (e.g., Pearson et al. 1998; Whelan 1996). These points are emphasized in Fig. 11, which shows a generic CPG in the vertebrate spinal cord (within the dashed rectangle) receiving primary afferent input and feedback from premotor interneurons as well as descending control of both rhythm generation and pattern formation functions. The arrows that inter-connect the elements do not reflect specific circuits but are meant to signify the complex interactions that are known to exist between spinal cord interneurons that act as nodal points for convergence of afferent and descending signals as well as the connections between premotor interneurons in reflex pathways (Jankowska 1992). Some of the arrows represent feedback loops between the elements within the CPG.
and premotor interneurons, which can adjust rhythm generation to match external conditions. In addition, all of the segmental elements project to supraspinal levels, where they enter multiple loops that project downward to control the segmental circuitry (Armstrong 1988; Arshavsky et al. 1988; Drew et al. 1996).

Hultborn and colleagues (1998) have emphasized the importance of rhythm resetting (persistent phase shift) by afferent input during fictive locomotion in determining whether a given reflex pathway has direct access to, or may even be part of, the rhythm-generating network in the locomotor CPG. Usually such resetting is produced by a short, high-frequency trains of afferent activation, although Currie and Stein (1988) demonstrated that relatively weak cutaneous stimulation can reset ongoing scratching rhythms in the spinalized turtle. In the present work, we attempted to avoid major disruptions of ongoing rhythms although, as stated earlier, we did not attempt to compare locomotor patterns with and without the low frequency, low amplitude stimuli used to probe reflex pathways.

FIG. 8. Averaged MPL EPSPs recorded from an EDL motoneurons in the same animal shown in Fig. 7. The pattern of spontaneous locomotion was similar to that shown in Fig. 7, A and B. In this cell, the disynaptic component of the MPL EPSP was suppressed throughout the flexion phase, irrespective of whether FDL or EDL was active. Up-modulation of disynaptic SP IPSPs during FDL activity in this cell has been published elsewhere (Degtyarenko et al. 1996, their Fig. 4).

FIG. 9. Independent cycling of extensor bursting with variable coupling to flexor motor pools. A: spontaneous stepping rhythm in which activity in the extensor LGS nerve waxed and waned with a period of –3 s with irregular interjection of brief flexion sequences (early short bursts in FDL and PBST and a longer, somewhat later burst in TA). The timing of these interjections was 1 per 2 extension cycles in the early part of the record and 1:1 in the 2nd half. Remarkably, the flexion sequences interrupted the extensor bursting rather than occurring between cycles and their presence or absence did not appear to alter the sinusoidal LGS periodicity. The FDL bursts were accompanied by depolarizing LDPs (→) with later hyperpolarization in the recorded FDL motoneuron (FDL IC). Stimulus artifacts, PSPs, and hyperpolarizing current pulses are grayed to emphasize the membrane potential trajectory. B: SP EPSPs averaged during flexion (F1–F3) to show the usual enhancement of the disynaptic (arrow) and trisynaptic components, largest in F1. The trisynaptic SP EPSPs averaged during periods with (“LGS on”) and without LGS firing (“LGS off”) were clearly smaller, although the latter was slightly larger than the former. C: the di- and trisynaptic MPL EPSPs were, as usual, completely suppressed during flexion phases, but the EPSPs during LGS off was slightly larger than during LGS on.
The following discussion is therefore confined to states of the CPG during the delivery of such probing stimuli.

**Possible wiring diagram**

The observations presented in this paper indicate that the locomotor CPG modulates oligosynaptic excitation of FDL motoneurons in different ways during fictive locomotion. The provisional wiring diagram in Fig. 12 attempts to tie together the various findings. This diagram should be considered as an extension of Fig. 11 because it omits the afferent and descending pathways that can influence rhythm generation and pattern formation. The CPG for locomotion (or any other coordinated, rhythmic movement) has two essential components: an oscillator to generate the basic rhythm and a system to shape that rhythm into a spatiotemporal pattern of signals to be delivered to the effector elements (Lennard and Hermanson 1985; Perret and Cabelguen 1980). In some invertebrate CPGs, these two functions are embodied in the same neural elements. For example, the network that generates, shapes, and executes the rhythms produced in the stomatogastric ganglion of crustacea is composed mostly of motoneurons (Selverston et al. 1998). The structure of the locomotor CPG in mammals remains unknown, although a variety of conceptual models have been advanced (reviewed in Grillner 1981; see also Stein and Smith 1997). Although it may be that some neural elements in the mammalian CPG contribute to both rhythm generation and pattern formation, we argue in the following text that the two functions are embodied, at least to some extent, in distinct neural circuits in the cat.

The diagram in Fig. 12 implies that the primary mechanism that produces modulation in reflex pathway EPSPs is convergence of afferent input and CPG drive onto common interneurons (Lundberg 1975). There is clear evidence that primary afferent depolarization (PAD), which is often associated with presynaptic inhibition, exhibits phasic variations during fictive locomotion (reviewed in Rossignol 1996). Although we cannot rule out some participation of presynaptic inhibition in the observed EPSP modulations, the evidence available suggests...
Rhythm generation is suggested by several pieces of evidence. Pattern formation may or may not also contribute to LDPs (see following text).

12), while others that belong to a variety of reflex pathways locomotor drive potentials in motoneurons (LDP INs in Fig. 3). The targets (last-order interneurons that excite or inhibit motoneurons) may be specialized to produce postsynaptic spatiotemporal sequence of commands. Some of the last-order rons) through a system of neurons that produce the required alternating half-center outputs are delivered to the ultimate targets (Fig. 12, thin dashed arrows). The half-centers are usually tightly interlocked (heavy arrows), but implying any specific neural circuitry. The flexor and extensor is the major mechanism responsible (Degtyarenko et al. 1998b; Moschovakis et al. 1991). We also cannot rule out the possibility that disinhibition could produce some of the excitatory effects implied by the arrows in the Fig. 12.

Rhythm generation

For the present purpose, we envision the rhythm generation function as embodied in two reciprocally organized half-centers represented by the split yin-yang symbol in Figs. 11 and 12. In agreement with Hultborn and colleagues (1998), we use the term “half-center” only as a convenient shorthand, without implying any specific neural circuitry. The flexor and extensor half-centers are usually tightly interlocked (heavy arrows), but under unusual conditions (e.g., Figs. 9 and 10), they can cycle with relative independence (Fig. 12, thin dashed arrows). The alternating half-center outputs are delivered to the ultimate targets (last-order interneurons that excite or inhibit motoneurons) through a system of neurons that produce the required spatiotemporal sequence of commands. Some of the last-order target interneurons may be specialized to produce postsynaptic locomotor drive potentials in motoneurons (LDP INs in Fig. 12), while others that belong to a variety of reflex pathways may or may not also contribute to LDPs (see following text).

Pattern formation

The existence of a pattern forming network separate from rhythm generation is suggested by several pieces of evidence. For example, the usual firing of FDL motoneurons, accompanied by depolarizing LDPs, can sometimes be suppressed by varying background afferent input with little change in the stepping rhythm (Figs. 3 and 4). More dramatically, FDL can sometimes be made to fire in either F1 or during extension by changing the steady afferent background, although this switch is often accompanied by changes in cycle durations (Fig. 6) (see also Degtyarenko et al. 1998a, their Fig. 8; Fleshman et al. 1984, their Figs. 7–11; Moschovakis et al. 1991, their Fig. 10). The fact that F1 facilitation of SP EPSPs in FDL motoneurons is observed whether or not the FDL motor pool is active in F1 or during extension (Figs. 5 and 6) seems best explained by postulating alternative circuits that are driven by, rather than integral to, the neural mechanism that produces the overall rhythm. Third, the apparent independent cycling of extensor (Fig. 9) and flexor half-centers (Fig. 10), with irregular emission of organized flexion or extension motoneuron bursts and associated modulation of reflex pathway interneurons, suggests that the interjected bursts are organized by circuits external to the rhythm generator and are triggered by it.

Finally, the available evidence indicates a rather precise sequencing of drive during the flexion phase that is delivered to FDL and other motoneurons as well as to last-order interneurons that project to them (Figs. 3A, 6A, 7, and 9A) (see also Burke 1999; Degtyarenko et al. 1996, 1998a,b; Moschovakis et al. 1991). The uniformly brief flexion bursts shown in Fig. 9 give the appearance of stereotyped event sequences that are triggered with variable phase relations to the LGS cycling rather than being shaped by the overall rhythm. In the usual form of fictive locomotion, FDL motoneurons are depolarized and fire only during the first third of the flexion phase (F1), and they are actively inhibited during the following two-thirds (F2 and F3; Figs. 3A, 4C, 6A, 7, and 9A). The F1 phase is also characterized by facilitation of transmission through the disynaptic excitatory SP pathway to FDL motoneurons (Figs. 4, 5, 6, 7, and 9) as well as facilitation of the disynaptic inhibitory pathway to EDL cells (Degtyarenko et al. 1996). The odd stepping pattern shown in Fig. 7 provides additional evidence that the pattern forming system that operates during F1 differ from that driving events later in flexion. We therefore suggest that the F1 → F2 → F3 sequencing (denoted by the arrow linking the F1 and F2 and F3 portions in Fig. 12) is controlled by mechanisms external to the rhythm generator. Although we cannot rule out some form of “ring” organization within the rhythm generation circuits themselves (Shik and Orlovsky 1976), the existence of independent cycling of flexor and extensor half-centers (Figs. 9 and 10) is difficult to reconcile with this idea.

Distribution of coordinated drive to motoneurons and interneurons

Locomotor drive from the pattern formation networks must eventually arrive at the appropriate targets at the correct moment during the step cycle. The fact that FDL motoneurons can fire during F1 or during extension, without disrupting the F2–F3 inhibition of these cells or the facilitation of the SP EPSP and the suppression of oligosynaptic MPL EPSPs (Figs. 5 and 6), suggests that the existence of neural circuits intermediate between the basic sequencing layer, represented by the
boxes in Fig. 12, and the target cells. The facultative operation of the pattern forming network is embodied in the switch included in the drive pathways between the F1 and Extension elements and the last-order excitatory LDP interneurons that drive FDL motoneurons.

Repetitive stimulation of low-threshold SP afferents during fictive stepping tends to favor the F1 firing behavior (Fig. 3) (Fleshman et al. 1984, their Fig. 10). On the other hand, repetitive MPL stimulation can either suppress this drive (Fig. 3) (see also Degtyarenko et al. 1998a, their Fig. 8) or, on some occasions, produce extension phase firing of FDL (Moschovakis et al. 1991, their Fig. 10). Stimulation of the sural nerve can also produce extension phase FDL firing (Fleshman et al. 1984, their Fig. 9). These observations suggest that afferent information has access to, and can modify, pattern formation, presumably to permit adaptive interactions between the centrally generated pattern and afferent information. Such relatively subtle effects of afferent input on pattern are included in Fig. 12 as thin dashed arrows linking SP and MPL afferents to the left switch. As noted in the preceding text, the diagram does not include the important mechanisms for resetting of locomotor rhythms (Hultborn et al. 1998; Pearson et al. 1998; Whelan 1996), which demonstrate that some afferent systems also have access to the rhythm generation elements in the locomotor CPG.

Locomotor control of transmission through the pathway from low-threshold MPL afferents and FDL motoneurons provides another example of state-dependent switching. In most examples of fictive stepping, di- and trisynaptic MPL EPSPs are powerfully suppressed throughout the flexion phase (Figs. 1 and 2), as symbolized in Fig. 12 by arrows from the F1 and F2–F3 boxes to inhibitory interneurons that project to the disynaptic cells in the MPL pathway. However, under some conditions, trisynaptic MPL EPSPs can be facilitated during the extension phase of fictive locomotion. This facilitation is sometimes linked to extensor phase FDL firing (Moschovakis

**Fig. 12.** Wiring diagram of the portion of the pattern generating part of the locomotor CPG that could produce the observed variable firing of FDL motoneurons and the modulation of oligosynaptic reflex arcs. The arrows denote inferred pathways or unspecified structures that have excitatory effects at their terminations.
et al. 1991, their Figs. 9 and 10), but this linkage is not always present (see Fig. 6D).

Although there is little evidence in the present material for stereotypical sequencing of extensor muscle activities and reflex pathway control during the extension phase of fictive stepping in out material, we include a complementary extension pattern formation network in the conceptual diagram in Fig. 12 because extensor phase sequencing clearly occurs in extensor muscles in the intact cat (e.g., Carlson-Kuhta et al. 1998). The extensor network enhances transmission of disynaptic group I EPSPs in FDL motoneurons (8/8 cells studied by Degtyarenko et al. 1998b; see also Angel et al. 1996, their Fig. 5), as it does in other cat hindlimb muscles, both flexor and extensor (Angel et al. 1996; Degtyarenko et al. 1998b; McCrea et al. 1995). Disynaptic EPSPs produced in FDL motoneurons by stimulation of the medial longitudinal fasciculus (MLF) in the brain stem are also facilitated exclusively during the extension phase, regardless of the phasing of FDL activity (not included in Fig. 12) (Degtyarenko et al. 1998a).

Are last-order interneurons part of the locomotor CPG?

With currently available information, it is impossible to define neurons that are “part” of the locomotor CPG versus neurons that are driven by it, particularly if some of the driven neurons have feedback access to the CPG per se (Fig. 11). Nevertheless, it seems logical to consider that last-order interneurons in reflex pathways, like motoneurons, are targets of CPG control rather than active participants in the rhythm and pattern formation networks. Some of these interneurons could contribute to LDPs when they receive excitatory drive coincident with depolarizing LDPs in the motoneurons, as is the case when disynaptic SP EPSPs are enhanced when FDL fires in F1. However, F1 enhancement of transmission in the SP pathway is sometimes dissociated from F1 depolarization in FDL motoneurons (Figs. 4 and 5), which requires us to postulate the existence of a separate group of excitatory LDP interneurons, as in Fig. 12. The interneurons that produced the oligosynaptic SP EPSPs in the LGS motoneuron shown in Fig. 10 could not have participated in the observed depolarizing LDPs in the cell, because the EPSPs were up-modulated out of phase with those LDPs.

On the other hand, stimulation of the MLR generates EPSPs with disynaptic segmental latencies in many types of motoneurons (Degtyarenko et al. 1998a; Shefchyk and Jordan 1985). These disynaptic MLR-evoked EPSP are generally enhanced during the phase of locomotion in which the recorded motoneurons is depolarized and active. This is also true of MLR EPSPs in FDL motoneurons, which are facilitated appropriately whether FDL is active in F1 or during extension (Degtyarenko et al. 1998a, their Fig. 8). This evidence is consistent with the idea that at least some of the last-order interneurons that generate depolarizing LDPs in FDL cells also receive direct descending input from the MLR (Fig. 12) (Jordan 1991; Shefchyk and Jordan 1985). It seems unlikely, however, that all such interneurons are “part” of the pattern formation function of the locomotor CPG, because the switching of depolarizing LDP drive to FDL cells appears to be accomplished at a relatively late stage of pattern formation (Fig. 12).

Structure of the locomotor CPG

The diagram in Fig. 12 is certainly overly simplified even for a scope limited to systems that project to the FDL motor pool. It is offered primarily as a framework for discussion of a potentially confusing array of observations and not as a comprehensive model of the CPG for locomotion in the cat spinal cord. The observations in this paper do not constrain models of rhythm generation that have been proposed by others (Grillner 1981; Jankowska et al. 1967; Lundberg 1975; Pearson 1981; Shik and Orlovsky 1976), except to suggest that the half-centers can at times operate semi-autonomously. Figure 12 does not include the cooperative interactions between the circuits that drive other segmental motor pools and other spinal segments, including the other limbs, or the influence of brain stem and cerebellum, which operate in the decerebrate preparation to produce output patterns that more closely resemble normal walking than those emitted by the isolated spinal cord (Armstrong 1988; Grillner 1981). It also does not include feedback from the pattern forming network to the rhythm-generating system (Fig. 11), which must be present to adapt the base frequency to the durations of the phased commands issued to target neurons.

On the other hand, the suggested schematic has the capacity to produce alternative patterns, embodied in the two switches, that are required to fit the two firing regimes exhibited by the FDL motor pool. Indeed, this versatility is the reason for our concentration on this motor nucleus, and it is also the feature that seems to require the kind of hierarchical CPG organization suggested in Fig. 12. In his seminal 1981 review on locomotion, Grillner (1981) discussed evidence that the spinal CPG for locomotion in mammals exhibits such a wide range of adaptive variability that it cannot be considered a “hard-wired” system. In recent years, the same plasticity has become evident even for the best-studied invertebrate CPGs (e.g., Harris-Warrick et al. 1998; Katz 1998; Selverston et al. 1998). Adaptability and alternative usage of shared circuits in the mammalian locomotor CPG, sometimes termed “modular organization” (Stein and Smith 1997; see also Getting 1989; Jordan 1991), is clearly implied in the present results and is therefore embodied in Fig. 12.

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