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Received June 12, 1993; Revised August 2, 1994; Accepted August 26, 1994.

Action Editor: Karen Sigvardt

Abstract. Rhythmic motor patterns can be induced in leg motor neurons of isolated locust thoracic ganglia by bath application of pilocarpine. We observed that the relative phases of levators and depressors differed in the three thoracic ganglia. Assuming that the central pattern generating circuits underlying these three segmental rhythms are probably very similar, we developed a simple model circuit that can produce any one of the three activity patterns and characteristic phase relationships by modifying a single synaptic weight. We show results of a computer simulation of this circuit using the neuronal simulator NeuralOGSpike. We built and tested an analog VLSI circuit implementation of this model circuit that exhibits the same range of "behaviors" as the computer simulation. This multidisciplinary strategy will be useful to explore the dynamics of central pattern generating networks coupled to physical actuators, and ultimately should allow the design of biologically realistic walking robots.

Introduction

Studies of central pattern generator models have demonstrated that neural circuits are not hardwired ensembles of neurons with fixed properties, but rather form plastic and adaptable sets. Different "functional" circuits can be formed from a fixed set of inter-connected neurons by altering neuronal and synaptic properties (Harris-Warrick et al., 1992; Harris-Warrick and Marder, 1991; Marder and Weimann, 1992). Some examples of neural circuits that are used to generate the motor patterns underlying multiple behaviors come from the studies of Tetzlaff's withdrawal and swimming (Getting and Dekin, 1985), crab forward and reverse scaphognathite beating (Simmers and Bush, 1983), Pleurobranchus feeding, regeneration, and rejection (McClanahan, 1982), and the crustacean gastric and pyloric nervous system (Weimann et al., 1991).

Work on more complex central pattern generators (such as the flight system of the locust (Robertson, 1986) or the spinal cord of vertebrates (Grillner et al., 1991; Grillner and Wallén, 1985) has shown that the identification of component neurons and their inter-connections do not necessarily yield a clear functional understanding of the circuits. An alternative strategy to exhaustive electrophysiological analysis of complex circuits and characterization of their component neurons is to use a limited experimental data set to generate artificial models, whose behavior can then be exhaustively challenged. This strategy, in time, leads to new specific questions about the biological system that can be addressed experimentally, and to the gradual addition of constraints on the modelled circuit. We adopted such a multidisciplinary strategy in the study of central pattern generating circuits underlying terrestrial locomotion in insects. We focussed on the thoracic circuits controlling the three pairs of legs of locusts. Because the front, middle, and hind legs have unique morphologies and functional roles during walking, we focussed here on the differences between the patterns of rhythmic activity generated by the three segments. Arguing that, although different, these rhythms should be produced by similar central pattern generating networks (the three thoracic ganglia being essentially homologous repeats of a single ontogenetic design), we then attempted to design a simplified generic circuit capable of producing all three output patterns. This paper describes one such successful circuit.

Although computer simulations are now widely used to model various aspects of neural systems, silicon (hardware) models are less commonly used. Yet silicon models are extremely useful in testing the ability
of a model to function with real physical constraints such as noise and device imperfections (Mead, 1989). In addition, the time-dependent operation in real time, feedback to the experimenter is immediate. Moreover, Very Large Scale Integrated (VLSI) circuits can be interfaced easily to mechanical actuators or biological systems which interact with the mobile robots (DeWeerth et al., 1991). Several types of spiking "neural" circuits have been successfully modelled in silicon hardware. Pulse stream encoding of information has been used in data communications applications and neural networks for a number of years (Murray et al., 1991; Mahowald et al., 1992). Ryckebusch et al. (1989) described silicon models of invertibrate central pattern generators using simple spiking neurons and synapses. Similar neuronal circuits have been used successfully in silicon models of auditory localization (Lazzaro and Mead, 1989) and the jamming-and-avoidance response of weakly-electric fish (LeMoncheck, 1992). A detailed model of a single neuron which explicitly included different membrane conductances and adaptation mechanisms was introduced by Mahowald and Douglas (1991). Our approach thus combined biological experiments, computer simulations, and silicon hardware designs, to study central pattern generators underlying terrestrial insect locomotion.

Methods

Electrophysiology

Experiments were performed on adult locusts Schistocerca americana of either sex, from our crowded laboratory colony. The results presented here were gathered from 44 different experiments.

The Preparation. Experiments were performed on an in vitro thoracic preparation described previously (Ryckebusch and Laurent, 1993). Briefly, thoracic ganglia were removed from the thorax of the animal with the surrounding tracheal supply and air sacs undisturbed, and were pinned down in a chamber lined with Sylgard (Dow Corning Co., Midland, MI). Leg motor nerves were carefully stripped of their surrounding connective tissue with a small hooked pin. The preparation was superfused with locust saline (mM: NaCl: 140; KCl: 5; CaCl2: 5; NaHCO3: 4; MgCl2: 1; 2,3-dihydroxy-4-hydroxypropanol-2-N-glutamyl-2-ethanesulfonic acid: 6.3; pH 7.0) supplemented with 2.5% (v/v) sucrose. Air was supplied to the ganglia by teasing open the trachea at the surface of the saline. A stock solution of 10−2 M pilocarpine hydrochloride (Sigma) was prepared in advance, and was added to the saline to final bath concentrations of 10−5 to 10−4 M. The preparation remained healthy for at least 4 or 5 hours at 20 to 26°C.

Recordings. The electrical activity of different leg motor nerves was monitored extracellularly using polyelectrolyte suction electrodes. Data were recorded on an eight-channel Digital Audio Tape recorder sampling at 5 Khz (Sony/Biologic), and were displayed on a Gould TA4000 chart recorder.

Anatomy and Nomenclature. The muscles are numbered according to Snodgrass (1929), except where a variant is now more commonly used in the literature. The nerves are numbered according to Brittain (1982). Motor neurons are designated by commonly used abbreviations or by the name of the muscle group that they innervate. Detailed descriptions of the innervation of the leg musculature can be found in Campbell (1961), Braunig (1982), and Siegel and Pousson (1990).

Analysis. Electrophysiological recordings were analyzed off-line using a Macintosh II microcomputer, after digitization at 2 to 8 Khz with a National Instruments NIMB016I AD/DA interface. The software packages used for data analysis were Spike Studio (Ell Meir, Cornell University), MadLab (The MathWorks), and Kaleidagraph (Abelbeck Software).

The centrally generated rhythm observed in the present experiments was characterized by two main phases, hereafter referred to as the levator and depressor phases, corresponding to the activities of levers and depressors of the trochanter. The onset of a burst of activity in trochanteral levator was chosen as the reference for the rhythmic activity. A period is defined as the interval from the onset of a levator burst to the onset of the next levator burst.

Computer Simulations

Spike: Event-Driven Simulation. "Spike" is a fast event-driven simulator written by Lloyd Watts (Caltech). Spike is an object-oriented simulation program that allows simple spiking neurons to be put together using a variety of flavors and combinations. Spike uses a very powerful and flexible simulation kernel for simulating spiking neurons and synapses. Spike is designed to be a flexible and fast simulator, which allows the user to easily modify and extend the kernel. Spike is also designed for use in both academic and industrial environments. Spike is written in C++ and is available for both Unix and Windows platforms.

The VLSI Implementation

The VLSI implementation of the neuron circuit contains 8 transistors and can operate over wide ranges straightforward to implement in VLSI a given model circuit which was designed and simulated using NeuRaLG. The VLSI implementation has been completed and the circuit has been fabricated. The circuit contains all of the components of the model neuron circuit. In addition, the circuit has been designed in such a way that it can be easily integrated into a larger system. The VLSI implementation of the neuron circuit is currently at the prototype stage and is being tested in a laboratory setting.
of a model to function with real physical constraints such as noise and device imperfections (Mead, 1989). In addition, time-dependent behavior operate in real time, feedback to the experimenter is immediate. Moreover, Very Large Scale Integrated (VLSI) circuits can be interfaced easily to mechanical actuators and body systems which interact with the mobile objects such as mobile robots (DeWeerth et al., 1991). Several types of spiking "neural" circuits have been successfully modeled in silicon hardware. Pulse stream encoding of information has been used in data communications applications and neural networks for a number of years (Murray et al., 1991; Mahowald et al., 1992). Ryckebusch et al. (1989) described silicon models of invertebrate central pattern generators using simple spiking neurons and synapses. Similar neuronal circuits have been used successfully in silicon models of auditory localization (Lazzaro and Mead, 1989) and the jamming avoidance response of weakly-electric fish (LeMoncheck, 1992). A detailed model of a single neuron which explicitly included different membrane conductances and adaptation mechanisms was introduced by Mahowald and Douglas (1991). Our approach thus combined biological experiments, computer simulations, and silicon hardware designs, to study central pattern generators underlying terrestrial insect locomotion.

Methods

Electrophysiology

Experiments were performed on adult locusts Schistocerca americana of either sex, from our crowded laboratory colony. The results presented here were gathered from 44 different experiments.

The Preparation. Experiments were performed on an in vitro thoracic preparation described previously (Ryckebusch and Laurent, 1993). Briefly, thoracic ganglia were removed from the thorax of the animal with the surrounding tracheal supply and air sacs undisturbed, and were pinned down in a chamber lined with Silgard 184 (Dow Corning Co., Midland, MI). Leg motor nerves were carefully stripped of their surrounding connective tissue with a small hooked pin.

The preparation was superfused with locust saline (mM: NaCl 140; KCl 5; CaCl2 2; NaHCO3 4; MgCl2 1; 1-N2-hydroxyethylpiperazine-N2-ethanesulfonic acid: 6.3; pH 7.0) supplemented with 2.5% (vivol) sucrose. Air was supplied to the ganglia by teasing open the tracheae at the surface of the saline. A stock solution of 10^-2 M pilocarpine hydrochloride (Sigma) was prepared in advance, and was added to the saline to final bath concentrations of 10^-3 to 10^-4 M. The preparation remained healthy for at least 4 or 5 hours at 20 to 26°C.

Recordings. The electrical activity of different leg motor nerves was monitored extracellularly using polyethylene suction electrodes. Data were recorded on an eight-channel Digital Audio Tape recorder sampling at 5 kHz (Sony/Biologic), and were displayed on a Good TA4000 chart recorder.

Anatomy and Nomenclature. The muscles are numbered according to Snodgrass (1929), except where a variant is now more commonly used in the literature. The nerves are numbered according to Brittin (1982). Motor neurons are designated by commonly used abbreviations or by the name of the muscle group that they innervate. Detailed descriptions of the innervation of the leg musculature can be found in Campbell (1961), Brittin (1982), and Siegler and Pousson (1990).

Analysis. Electrophysiological recordings were analyzed off-line with a Macintosh II microcomputer, after digitization at 2 to 8 kHz with a National Instruments NIB0016 AD/DA interface. The software packages used for data analysis were Spike Studio (Elife Meirc, Cornell University), MultiLab (The MathWorks), and Kaleidagraph (Abelbeck Software).

The centrally generated rhythm observed in the present experiments was characterized by two main phases, hereafter referred to as the levator and depressor phases, corresponding to the activities of levators and depressors of the trochanter. The onset of a burst of activity in trochanteral levators was chosen as the reference for the rhythmic activity. A period is defined as the interval from the onset of a levator burst to the onset of the next levator burst.

Computer Simulations

Spike: Event-Driven Simulation. "Spike" is a fast event-driven simulator written by Lloyd Watts (California Institute of Technology, Pasadena, CA). It is a simulator of spiking neurons and synapses. The key simplifying assumption in Spike is that all currents injected into a cell may be decomposed into piecewise-constant pulses (i.e., boxcar pulses). All integrated membrane voltage trajectories are therefore piecewise linear in time. This simple representation is well-suited for investigating system-level questions that rely on detailed spiking behavior. The simulator operates by maintaining a queue of scheduled events. The occurrence of one event (i.e., an action potential) usually causes later events to be scheduled in the queue (i.e., end of refractory period, end of post-synaptic current pulse). The total current injected into a neuron is integrated into the future to predict the time of firing, at which time a neuron spike event is scheduled. If any of the current components being injected into the cell subsequently change, the spike event is rescheduled. The simulator runs until the queue is empty or until the desired run-time has elapsed.

NeuralOG: Neural Schematic Capture. "NeuralOG" is a schematic entry tool, which allows the convenient entry of "neural" circuit diagrams, consisting of primitive circuit elements such as neurons, synapses, test inputs, and custom symbols. NeuralOG is a customized by Lloyd Watts of the program AnaLOG, by John Lazzaro and Dave Gillespie (Caltech). The parameters of the neural elements are entered directly on the schematic diagrams; these parameters include the neuron refractory period, duration and intensity of the post-synaptic current pulse following an action potential, saturation value of summing post-synaptic currents, tonic input currents, axonal delays, and so on. Custom symbols can be defined, so that arbitrarily complex hierarchical designs may be made. For example, using existing primitive circuit elements as building blocks, one can create a complex "neuron" (e.g., bursting neuron). A custom symbol can be created to represent this complex "neuron," which can then be used as a building block in another circuit. Spiking inputs may be supplied as external stimuli in a number of formats, including single spikes, periodic spike trains, periodic bursts, Poisson random spike trains, and Gaussian-jittered periodic spike trains. Test inputs to Spike is also possible, to allow simulation of algorithmically-generated circuit topologies too complex to specify graphically.

NeuralOG and Spike were both created by Lloyd Watts, and are distributed under the GNU General Public Licence. Send email to lloyd@pclp.caltech.edu for information.

Models and Synapse Models. The model neuron and synapse circuit primitives we used both in our simulations and in the VLSI implementation were developed by John Lazzaro and are described somewhere of the basic characteristics of biological neurons and synapses. These circuit elements are the primitive elements in the NeuralOG/Spike simulator described above. Since both the neuron and synapse circuits were designed as electronic VLSI circuits, it is relatively straightforward to implement in VLSI a given model circuit which was designed and simulated using NeuralOG/Spike. Detailed mathematical analysis of the neuron circuit at the transistor level can be found in Surpeth et al. (1992). General descriptions of the circuit models and the simulation tools can be found in Watts (1992, 1994). Below we will describe these circuits here in biological terms. The model neuron circuit is similar to a Hodgkin-Huxley sodium-potassium conductance pair. This neuron circuit takes as its input a current, and generates as its output a train of pulses whose height is determined by the voltage of the power supply (typically 5 volts). The pulses are fired only if the input node, which is integrating the input current, reaches the threshold voltage. The firing frequency increases with the input current until the upper frequency limit (saturation) set by the refractory period is reached. The neuron circuit has three parameters: a threshold, a pulse width, and the refractory period of the action potential. The circuit operations underlying the generation of a pulse can be described in biological terms as follows. A persistent "sodium conductance" causes the rising phase of the action potential. The "sodium conductance" activates after a delay, a "potassium conductance" that is coupled to it. This "potassium conductance" restores the membrane potential to its "resting" value and causes the falling phase of the action potential. A simplified spiking cell model is the basis for the circuit diagrams. An action potential generated by the preysynaptic neuron causes the release of "neurotransmitter" into the synaptic cleft, where it remains for a controlled duration. While the "neurotransmitter" is in the cleft, a constant current is injected into the postsynaptic cell. The "synaptic" circuit therefore has two parameters: the duration of a synaptic event and the synaptic conductance which flows into the postsynaptic cell. Any number of "synapses" can be connected to a "neuron" circuit. In addition, although this basic integrate-and-fire neuron is a primitive building block of the computational, a complex "neurons" can be created by forming small circuits composed of these building blocks.

VLSI Implementation

The VLSI implementation of the neuron circuit contains 8 transistors and can operate over wide ranges.
of firing frequency, pulse width, refractory period, and threshold. The firing frequency can be varied from 0.1-0.5 Hz to 100 kHz. The pulse widths and refractory periods of the action potentials can be varied from a few tens of microseconds to hundreds of milliseconds. The threshold for firing can be varied from approximately 0.7 volts to the power supply voltage (5 volts). A typical neuron with its synaptic inputs measures approximately 100 x 250 μm. The entire 3-neuron circuit contains 97 transistors and measures 400 x 600 μm. VLSI circuits were designed using the layout editor Ledit (Tanner Research) on a Hewlett Packard workstation. The chip was fabricated in a standard 2-micron double-poly CMOS (Complementary Metal-Oxide Semiconductor) process on a 2 x 2 mm 40-pin die (TinyChip) (Fig. 7). Chip fabrication was provided by the Defense Advanced Research Projects Agency and through the MOSIS service. Data acquisition was performed using a Macintosh microcomputer with a National Instruments NIBMIO16L AD/DA interface running Matlab (The MathWorks).

**Abbreviations**

CI common inhibitor
CMOS Complementary Metal-Oxide Semiconductor
dep depressor
D<br/>f fast depressor trochanteris
D<br/>l slow depressor trochanteris
lev levator
troch trochanter
VLSI Very Large Scale Integrated

**Results**

**Pro-, Mes-, and Metathoracic Ganglia Produce Different Rhythmic Patterns**

**Metathoracic Rhythm.** The rhythmic patterns evolved in leg motor neurons in isolated metathoracic ganglia by pilocarpine have been described in detail in Rykebusch and Laurent (1993). Those results are summarized here for the purposes of comparison.

The frequency of the pilocarpine-induced rhythm increased approximately linearly from 0 to 0.2 Hz with concentrations of pilocarpine from 10^{-5} to 10^{-4} M. For each hemiganglion, the rhythm was characterized by two main phases: a *levator* phase, during which the anterior coxal rotator, levators of the trochanter, flexors of the tibia, and common inhibitory motor neurons were active, and a *depressor* phase, during which depressors of the trochanter, extensors of the tibia, and depressors of the tarsus were active. During normal walking these two phases would correspond to the swing and stance phases of a step of the hind leg, respectively. Trochanteral depressor activity followed the trochanteral levator bursts with a short, constant interburst latency such that activity in the two antagonistic groups did not overlap. The levator phase was short in comparison to the cycle period (0.5 to 2 sec, or 5% to 20% of the period), and was independent of the cycle period. The interval between the end of a levator burst and the beginning of the following one thus increased with cycle period. The depressor phase was more variable, and was usually shorter than the interval between successive levator bursts. A second depressor burst was sometimes observed during the latter half of a cycle. This second burst generally coincided with a levator burst on the contralateral side and always ended before the onset of the ipsilateral levator burst.

All depressor trochanteris motor neurons were active during the same phase, although their spiking thresholds differed substantially. In inactivations preparations (no pilocarpine), Df was silent and Dl was tonically active. At low levels of activity, the tonic firing of Dl was interrupted during the bursts of trochanteral levator activity; this interval was followed by a transient increase in firing frequency. Variations of the instantaneous firing frequency of Dl were mirrored by those of the membrane potential of Df, which was hyperpolarized during a levator burst, and depolarized immediately after it. As the level of activity increased, the tonic firing of Dl ceased, and short, clearly defined bursts of action potentials emerged. Df action potentials were often observed when Dl reached its peak instantaneous firing frequency.

**Prothoracic Rhythm.** We recorded extracellularly from leg motor nerves 4A (trochanteral levators) and 5A (trochanteral depressors) of isolated prothoracic ganglia. From nerve 4A, we recorded the activity of up to 10 motor neurons. From nerve 5A, we recorded the activity of the fast and slow trochanteral depressors Dl and Df, and a common inhibitory motor neuron CI. Depolarization of Df was silent and Dl was tonically active. The prothoracic rhythmic motor patterns recorded in the presence of pilocarpine differed in several respects from the metathoracic ones. During rhythmic activity, Dl maintained a high tonic firing rate, and was periodically inhibited during the bursts of trochanteral levator activity (Fig. 1 (top)). The rhythmic activity could be elicited at lower concentrations of pilocarpine (ca. 10^{-3} M) than that which was typically used for the metathoracic ganglion (5 x 10^{-3}-10^{-4} M). The frequencies (inverse of cycle period) typically recorded were higher than those in the metathoracic ganglion at similar concentrations of pilocarpine. Although both prothoracic trochanteral levator burst durations and interburst intervals were shorter than the metathoracic ones, the higher frequency was mainly due to shorter intervals between trochanteral levator bursts (Figs. 1 and 2). Whereas metathoracic Df and Dl fired at the highest rate immediately after a
of firing frequency, pulse width, refractory period, and threshold. The firing frequency can be varied from 0.1–0.5 Hz to 100 kHz. The pulse widths and refractory periods of the action potentials can be varied from a few tens of microseconds to hundreds of milliseconds. The threshold for firing can be varied from approximately 0.7 volts to the power supply voltage (5 volts). A typical neuron with its synaptic inputs measures approximately 100 × 250 μm. The entire 3-neuron circuit contains 97 transistors and measures 400 × 600 μm. VLSI circuits were designed using the layout editor LEDit (Tanner Research) on a Hewlett Packard workstations. The chip was fabricated in a standard 2-micron double-poly CMOS (Complementary Metal-Oxide Semiconductor) process on a 2 × 2 mm 40-pin die (TinyChip) (Fig. 7). Chip fabrication was provided by the Defense Advanced Research Projects Agency and through the MOSIS service. Data acquisition was performed using a Macintosh microcomputer with a National Instruments NIBIO16L AD/DA interface running MatLab (The MathWorks).

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Results

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Metathoracic Rhythm. The rhythmic patterns evolved in leg motor neurons in isolated metathoracic ganglia by pilocarpine have been described in detail in Rycekbusch and Laurent (1993). Those results are summarized here for the purposes of comparison. The frequency of the pilocarpine-induced rhythm increased approximately linearly from 0 to 0.2 Hz with concentrations of pilocarpine from 10^{-5} to 10^{-4} M. For each hemiganglion, the rhythm was characterized by two main phases: a levator phase, during which the anterior coxal rotator, levators of the trochanter, flexors of the tibia, and common inhibitory motor neurons were active and a depressor phase, during which depressors of the trochanter, extensors of the tibia, and depressors of the tarsus were active. During normal walking these two phases would correspond to the swing and stance phases of a step of the hind leg, respectively. Trochanteral depressor activity followed the trochanteral levator bursts with a short, constant interburst latency such that activity in the two antagonistic groups did not overlap. The levator phase was short in comparison to the cycle period (0.5 to 2 sec, or 5% to 20% of the period), and was independent of the cycle period. The interval between the end of a levator burst and the beginning of the following one thus increased with cycle period. The depressor phase was more variable, and was usually shorter than the interval between successive levator bursts. A second depressor burst was sometimes observed during the latter half of a cycle. This second burst generally coincided with a levator burst on the contralateral side and always ended before the onset of the ipsilateral levator burst.

All depressor trochanteris motor neurons were active during the same phase, although their spiking thresholds differed substantially. In inactive preparations (no pilocarpine), D₂ was silent and D₁ was tonically active. At low levels of activity, the tonic firing of D₁ was interrupted during the bursts of trochanteral levator activity; this interruption was followed by a transient increase in firing frequency. Variations of the instantaneous firing frequency of D₁ were mirrored by those of the membrane potential of D₂, which was hyperpolarized during a levator burst, and depolarized immediately after it. As the level of activity increased, the tonic firing of D₁ ceased, and short, clearly defined bursts of action potentials emerged. D₁ action potentials were often observed when D₁ reached its peak instantaneous firing frequency.

Prothoracic Rhythm. We recorded extracellularly from leg motor nerves 4A (trochanteral levators) and 5A (trochanteral depressors) of isolated prothoracic ganglia. From nerve 4A, we recorded the activity of up to 10 motor neurons. From nerve 5A, we recorded the activity of the fast and slow trochanteral depressors D₁ and D₂, and a common inhibitory motor neuron CI. From nerve 4A, pilocarpine (10^{-4} M) caused a significant increase in the firing rate of D₁ and D₂, and the other motor neurons. From nerve 5A, pilocarpine (10^{-4} M) caused a decrease in the firing rate of CI. The frequencies of the prothoracic rhythm were typically higher than those of the metathoracic ganglia at similar concentrations of pilocarpine. Although both prothoracic trochanteral levator burst durations and interburst intervals were shorter than the metathoracic ones, the higher frequency was mainly due to shorter intervals between trochanteral levator bursts (1 to 2 sec). As a result, the prothoracic rhythm was typically recorded at lower concentrations of pilocarpine than in the metathoracic ganglion.
The latency between the end of a levator burst and resumption of tonic firing of $D_I$ was shorter than that observed in the metathoracic ganglion (Fig. 2). Whereas in the metathoracic ganglion we often saw coupling between depressors and the contralateral levators (i.e., the firing frequency of depressors increased during a contralateral levator burst), we rarely saw such bilateral coupling in the prothoracic ganglion. A detailed analysis of intersegmental coupling is described in another publication (Ryckebusch and Laurent, 1994).

**Fig. 2.** Spike frequency histograms of prothoracic levator and depressor motor neuron activity as shown in Fig. 1. Data is compiled from 30 (pro), 132 (meso) and 53 (meta) periods of activity from single continuous recordings. The reference is the onset of a burst of prothoracic levator action potentials. The scale on the ordinate is the total number of action potentials in each bin, and represents a cumulative total for all of the periods of activity that were analyzed.

Fig. 3. Comparison of rhythmic activity in thoracic levator motor neurons for pro-, meso-, and metathoracic ganglia. All graphs were obtained from single continuous recordings of nerve 4A (pro and meso) or 382 (meta) in three separate preparations of isolated single ganglia. Top graphs are cycle period of thoracic levators as a function of onset time of the burst. Each cycle period was measured as the length of the interval between onset of consecutive levator bursts. Bottom graphs are duration of levator burst as a function of the cycle period following the occurrence of that burst. The same data was used both in the bottom and top graphs, for each ganglion. Prothoracic: $7 \times 10^{-5}$ M (pro and meso); $7 \times 10^{-1}$ M (meta). Average periods in seconds: 9.543 ± 1.727 (pro); 9.157 ± 1.863 (meso); 16.472 ± 4.810 (meta). Average burst durations in seconds: 1.011 ± 0.174 (pro); 0.657 ± 0.128 (meso); 0.929 ± 0.100 (meta).

**Metathoracic Rhythm.** The rhythmic activity recorded in the metathoracic ganglion was similar in most respects to that in the prothoracic ganglion, as described above. The main difference observed was that the depressor motor neurons ($D_I$ and $D_{II}$) had marked peaks of activity both immediately before and after a levator burst (Figs. 1 and 2). This pattern of activity was somewhat variable: in some preparations, the metathoracic depressors fired maximally before the levator burst (as was described for the prothoracic ganglion); in other preparations, the depressors fired maximally after a levator burst (as was observed in the metathoracic ganglion); in still other preparations, depressor activity was equally high both before and after a levator burst. In most preparations, each of these patterns occurred at some time. Because these output patterns tended to vary in an unpredictable way both in time and between preparations, a meaningful statistical measure of the occurrence of different patterns could not be devised. The frequencies of the rhythmic activity were similar to those of the prothoracic ganglion, as described above.

Some of the characteristics of the prothoracic levator activities (in pro-, meso-, and metathoracic ganglia) are shown in Fig. 3, obtained from recordings of three different isolated thoracic ganglia. In all three thoracic ganglia, the durations of the levator bursts are independent of the cycle period (Fig. 3, bottom 3 traces). In addition, this duration is short compared to the total cycle period (5–115% here). Although the concentration of picrotoxin was much higher in the metathoracic ganglion ($7 \times 10^{-3}$ M) than the pro- or mesothoracic ganglia ($10^{-3}$ M), the frequency of the
trochanteral levator burst, the highest firing frequency of prothoracic Dₐ and Dᵧ occurred before trochanteral levator bursts (Figs. 1 and 2). Overlap between levator and depressor activities was often observed at the beginning of a trochanteral levator burst (Fig. 2). In the isolated prothoracic ganglion, we typically did NOT observe a postinhibitory increase in depressor firing frequency after a trochanteral levator burst, although the latency between the end of a levator burst and resumption of tonic firing of Dᵧ was shorter than that observed in the metathoracic ganglion (Fig. 2). Whereas in the metathoracic ganglion we often saw coupling between depressors and the contralateral levators (i.e., the firing frequency of depressors increased during a contralateral levator burst), we rarely saw such bilateral coupling in the prothoracic ganglion. A detailed analysis of intersegmental coupling is described in another publication (Ryckebech and Laurent, 1994).

Mesothoracic Rhythm. The rhythmic activity recorded in the mesothoracic ganglion was similar in most respects to that in the prothoracic ganglion, as described above. This difference was observed in that the depressor motor neurons (Dᵧ and Dₛ) had marked peaks of activity both immediately before and after a levator burst (Figs. 1 and 2). This pattern of activity was somewhat variable: In some preparations, the mesothoracic depressors fired maximally before the levator burst; in other preparations, the depressors fired maximally after a levator burst (as was observed in the metathoracic ganglion); in still other preparations, depressor activity was equally high both before and after a levator burst. In most preparations, each of these patterns occurred at some time. Because these patterns tended to vary in an unpredictable way both in time and between preparations, a meaningful statistical measurement of the occurrence of different patterns could not be devised. The frequencies of the rhythmic activity were similar to those of the prothoracic ganglion, as described above.

Some of the characteristics of the trochanteral levator activities (pro-, meso-, and metathoracic ganglia) are shown in Fig. 3, obtained from recordings of three different isolated thoracic ganglia. In all three thoracic ganglia, the durations of the levator bursts are independent of the cycle period (Fig. 3, bottom traces). In addition, this duration is short compared to the total cycle period (5–11% here). Although the concentration of pilocarpine was much higher in the metathoracic ganglion (7 × 10⁻⁸ M) than the pro- or mesothoracic ganglia (10⁻⁶ M), the frequency of the
metathoracic rhythm was much lower than the other thoracic rhythms.

The thoracic patterns described above are the only patterns which were seen consistently in every preparation of the corresponding thoracic ganglion, although they did not occur continuously in any preparation, and other patterns were also observed. The proportion of cycles in each preparation which showed the "typical" pattern was different in each preparation, and changed over time within a given preparation. These patterns were chosen as "typical" because they were the only recognizable patterns which occurred regularly in all preparations.

A Simple Configurable Model Circuit

The aim of the simulation studies described here was to test model circuit designs which could produce the different motor patterns recorded in the isolated pro-, meso-, and metathoracic ganglia. The goal of this modeling study was therefore to explore possible circuit designs of a central pattern generator which would be flexible enough to produce all of these motor patterns using simple and biologically realistic mechanisms in the model circuit. Such a circuit was designed using abstract models of neurons and synapses using the NeuralGOSpike circuit simulator (see Methods). It should be emphasized that this circuit was designed so that it would be both simple and easy to implement using available VLSI technology (see below).

The Bursting Neuron. A bursting neuron, which produces rhythmic bursts of action potentials, was constructed using two primitive integrate-and-fire neuron circuits (which we call cell 1 and cell 2) to avoid confusion. Two neuron circuits were needed to obtain an equivalent neuron with enough state variables to generate bursting behavior. In the bursting circuit (Fig. 4A), cell 1 makes a weak excitatory synapse onto cell 2. Cell 2, in turn, makes a strong inhibitory synapse onto cell 1. In addition, cell 1 makes an excitatory feedback synapse onto itself. In response to an excitatory input drive (such as a constant current or a train of action potentials fed through an excitatory synapse), cell 1 fires bursts of action potentials. The activity of cell 1 is taken to be the output of the bursting neuron. The firing frequency of cell 1 during a burst is determined by the magnitude of its positive feedback current. The duration of the burst is determined by the strength of the excitatory synapse from cell 1 to cell 2, and the interval between bursts is determined by the strength of the excitatory input drive to cell 1. The burst duration and interburst interval are therefore independently determined.

The Central Pattern Generator Circuit. The entire model circuit, shown in Fig. 4B, is composed of two bursting neurons as described above (OSC and LEV) and one non-bursting neuron (DEP). LEV represents the drive to the pool of trochanteral levator motor neurons, and DEP represents the drive to the pool of trochanteral depressor motor neurons. For simplicity, we will often refer to DEP and LEV as levator and depressor drivers. Since connections between motor neurons occur only exceptionally in locust circuits, we consider levator and depressor motor neurons to be follows, rather than fundamental components of the central pattern generating circuits. The connections shown between LEV and DEP in the model circuit are therefore not connections between pools of motor neurons, but between the central drives to these motor neurons.

In this model circuit, OSC makes excitatory synapses onto LEV and DEP, and LEV makes an inhibitory synapse onto DEP. The ability of this circuit to produce the different patterns of levator and depressor activity depends on the relative strengths of the excitatory synapses, $I_1$ and $I_2$. In particular, by simply modifying the strength of $I_2$, the output of the circuit can be changed from a prothoracic-like pattern, where the activity of DEP precedes LEV, to a metathoracic-like pattern, where the activity of DEP follows the activity of LEV. Intermediate mesothoracic-like patterns are obtained in the transition region between prothoracic and metathoracic patterns. The operation of the model circuit can be understood as follows: OSC receives a constant depolarizing input, which causes it to burst rhythmically (see previous description of bursting neurons). When OSC is active, it excites both LEV and DEP. If $I_2$ is weaker than $I_1$, DEP reaches threshold sooner than LEV, and fires as long as it is being driven. Once LEV reaches threshold, it fires a burst of action potentials, inhibiting DEP. Since LEV is a bursting neuron, its burst of activity eventually ends. This first pattern, shown in Fig. 5 (PRO), is similar to the prothoracic rhythmic pattern described above (Figs. 1 and 2). Note that Fig. 5 shows the outputs of two different depressor drivers (a "fast" depressor DEP, and a "slow" depressor DEP,) with different thresholds. The activities of these drivers differ only in that DEP, fires tonically in its resting state. Compare with the activities of the biological motor neurons $D_f$ and $D_s$ (Fig. 1, lower traces).

If, on the other hand, $I_2$ is stronger than $I_1$, LEV reaches threshold sooner than DEP. Once LEV begins to spike, DEP is inhibited. Only when LEV stops firing is DEP released from inhibition sufficiently to fire a burst of action potentials. This pattern, shown in Fig. 5 (META), is similar to the metathoracic rhythmic pattern described above and shown in Figs. 1 and 2. In order for DEP to fire a burst of action potentials upon release from inhibition, it must receive sufficient excitatory input to drive it to threshold. This can be accomplished in this model circuit in either of two ways. (i) If OSC has a longer burst duration than LEV ($\text{OSC} \gg \text{LEV}$), DEP will continue to receive excitatory input from OSC once it is no longer being inhibited by LEV. This is a simple condition to achieve, since the burst durations of OSC and LEV can be controlled independently. If, however, the burst duration of OSC is set too long, LEV may be depolarized enough to generate another burst, leading to an alternating "double-burst" in the activity of LEV. (ii) In the simulation, the excitation to DEP was prolonged by making the time constant of decay of the excitatory current $I_2$ very long. As a consequence, DEP is being depolarized by a persistent excitatory current for a certain time $t_2$ after
metathoracic rhythm was much lower than the other thoracic rhythms.

The thoracic patterns described above are the only patterns which were seen consistently in every preparation of the corresponding thoracic ganglion, although they did not occur continuously in any preparation, and other patterns were also observed. The proportion of cycles in each preparation which showed the "typical" pattern was different in each preparation, and changed over time within a given preparation. These patterns were chosen as "typical" because they were the only recognizable patterns which occurred regularly in all preparations.

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In this model circuit, OSC makes excitatory synapses onto LEV and DEP, and LEV makes an inhibitory synapse onto DEP. The ability of this circuit to produce the different patterns of levator and depressor activity depends on the relative strengths of the excitatory synapses, $I_L$ and $I_D$. In particular, by simply modifying the strength of $I_L$, the output of the circuit can be changed from a prothoracic-like pattern, where the activity of DEP precedes LEV, to a metathoracic-like pattern, where the activity of DEP follows the activity of LEV. Intermediate mesothoracic-like patterns are obtained in the transition region between prothoracic and metathoracic patterns. The operation of the model circuit can be understood as follows: OSC receives a constant depolarizing input, which causes it to burst rhythmically (see previous description of burster neuron). When OSC is active, it excites both LEV and DEP. If $I_L$ is weaker than $I_D$, DEP reaches threshold sooner than LEV, and fires as long as it is being driven. Once LEV reaches threshold, it fires a burst of action potentials, inhibiting DEP. Since LEV is a bursting neuron, its burst of activity eventually ends. This first pattern, shown in Fig. 5 (PRO), is similar to the prothoracic rhythmic pattern described above (Figs. 1 and 2). Note that Fig. 5 shows the outputs of two different depressor drivers (a "fast" depressor DEP, and a "slow" depressor DEP,) with different thresholds. The activities of these drivers differ only in that DEP fires tonically in its resting state. Compare with the activities of the biological motor neurons $D_f$ and $D_s$ (Fig. 1, lower traces).

If, on the other hand, $I_L$ is stronger than $I_D$, LEV reaches threshold sooner than DEP. Once LEV begins to spike, DEP is inhibited. Only when LEV stops firing is DEP released from inhibition sufficiently to fire a burst of action potentials. This pattern, shown in Fig. 5 (META), is similar to the metathoracic rhythmic pattern described above and shown in Figs. 1 and 2. In order for DEP to fire a burst of action potentials upon release from inhibition, it must receive sufficient excitatory input drive to threshold. This can be accomplished in this model circuit in either of two ways. (i) If OSC has a longer burst duration than LEV ($w_{OSC} > w_{LEV}$), DEP will continue to receive excitatory input from OSC as it is no longer being inhibited by LEV. This is a simple condition to achieve, since the burst durations of OSC and LEV can be controlled independently. However, the burst duration of OSC is set too long, LEV may be depolarized enough to generate another burst, leading to incorrect "double bursts" in the activity of LEV. (ii) In the simulation, the excitation to DEP was prolonged by making the time constant of decay of the excitatory current $I_D$ very long. As a consequence, DEP is being depolarized by a persistent excitatory current for a certain time $t_2$ after

![Fig. 4](image-url)
the OSC burst terminates. The mathematical analysis shown in Appendix A is general enough to allow one or both of the conditions to hold.

For intermediate values of the synaptic strength $I_{s}$, DEP fires a burst of action potentials both before and after a burst of activity in LTV. This output is therefore similar to the mesothoracic rhythmic pattern (Figs. 1, 2, and 5).

Spine frequency histograms of the simulation output are shown in Fig. 6. This figure should be compared with Fig. 2, which shows the spine frequency histograms of electrophysiological data from locust thoracic ganglia. One major difference between the figures is the shape of the spine frequency histogram. This histogram is bell-shaped in Fig. 2, whereas it is square in Fig. 6. This difference is mainly due to the different numbers of neurons whose activity is represented in the histograms. In Fig. 2, data was obtained by pooling all of the thronchaleuralevator potential actions on nerve 4A, which included up to 10 motor neurons with different thresholds. As can be seen from Figure 1, a thoracalerlevator burst consists of action potentials from many different motor neurons, with the largest number of neurons participating near the middle of the burst. In contrast, the simulation in Fig. 6 only included a singlelevator driver (LEV). A similar bell-shaped distribution would be obtained by pooling the activities of many levator motor neurons driven by LEV, but with different thresholds.

In Fig. 2, substantial overlap between activities of the levators and depressors of the thoracalerlevator can be seen, particularly for the pro- and mesothoracic patterns. This overlap is much smaller in the simulation histograms in Fig. 6. Such overlap can be obtained in the simulation by weakening the inhibition between the levators and depressors, which would allow some co-activity between the antagonists (Fig. 4B).

**VLSI Implementation**

We designed, fabricated, and tested a VLSI implementation of the simulated model circuit described above (see Methods). The entire chip layout is shown in Fig. 7. The electronic circuit implemented on the chip was essentially the same as the simulated circuit, since, as described in Methods, the circuit primitives used in the simulator were developed on the basis of existing electronic circuits. The different parameters in the model were represented as voltages which could be externally controlled. The synaptic strength $I_{s}$ (Fig. 4B) was represented as a single voltage parameter. Figure 8 shows voltage across the chip operating at different frequencies. Figure 9A, for example, shows the output from the levator and depressor drivers for three different values of $I_{s}$. As was shown in the simulation (Figs. 5 and 6), as $I_{s}$ is increased, the output of the circuit moves smoothly from a prothoracic (top) to a mesothoracic (middle), and finally to a thoracalerlevator (bottom) rhythmic pattern. All other circuit parameters were unchanged. Figures 8B and 8C show the same behavior as Fig. 9A, but at different time scales. In each case, the circuit parameters were adjusted for operation of the circuit at a given time scale, but only $I_{s}$ was then modified to generate the pro-, meso-, and thoracalerlevator rhythmic patterns. We verified that the chip can operate in a stable manner in the frequency range of 0.1 to 100 Hz.

The circuit was most stable (i.e., the operating range of circuit parameters was widest) at higher frequencies of operations. In an attempt to quantifying the decreased circuit stability at lower frequencies of operation, we studied the operating range of a single parameter ($I_{s}$) for different time scales of circuit operation (Fig. 9). We chose the synaptic current $I_{s}$, since it is this parameter that determines the output of the circuit model. For each frequency of circuit operation, we measured the amount by which $I_{s}$ needed to be changed to switch from a prothoracic to a mesothoracic pattern (defined to be the "range" of $I_{s}$). On the chip, $I_{s}$ is determined by externally setting the voltage on the gate of a single transistor. Since the synaptic currents in the chip could not be measured, $I_{s}$ was estimated from the gate voltage and was normalized. The range of $I_{s}$ was determined for different frequencies of circuit operation and decreased monotonically as the cycle period increased (Fig. 9). This is because slow operation of the circuit is achieved by reducing all currents in the electronic circuit. Therefore, excitations in the circuits are needed to switch between two states are correspondingly smaller. Since all of the currents in the circuit are smaller at lower frequencies, we would expect the operating range of all of the different circuit parameters to decrease in a similar way. This decrease in operating range of the parameters is closely related to the increased instability of the circuit at lower frequencies. When currents are very small, instabilities due to noise and device imperfections have a greater effect on circuit operation. These instabilities can be avoided by operating the circuit near the middle of its dynamic range. One feature of both the computer simulation and
the OSC burst terminates. The mathematical analysis shown in Appendix A is general enough to allow one or both of the conditions to hold.

For intermediate values of the synaptic strength $I_2$, DIEF fires a burst of action potentials both before and after a burst's activity in LEV. This output is therefore similar to the mesothoracic rhythmic pattern (Figs. 1, 2, and 5).

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The circuit was most stable (i.e., the operating range of circuit parameters was widest) at higher frequencies of operations. In an attempt to quantify the decrease in circuit stability at lower frequencies of operation, we studied the operating range of a single parameter ($I_2$) for different time scales of circuit operation (Fig. 9). We chose the synaptic current $I_2$, since this is the parameter that determines the output of the circuit model. For each frequency of circuit operation, we measured the amount by which $I_2$ needed to be changed to switch from a prothoracic to a metamorphic pattern (defined to be the "range" of $I_2"). On the chip, $I_2$ is determined by externally setting the voltage on the gate of a single transistor. Since the synaptic currents in the chip could not be measured, $I_2$ was estimated from the gate voltage and was normalized. The range of $I_2$ was determined for five different frequencies of circuit operation and decreased monotonically as the cycle period increased (Fig. 9). This is because slow operation of the circuit is achieved by reducing all currents in the electronic circuit. Therefore, excitations in circuit parameters needed to switch between two states are correspondingly smaller. Since all of the currents in the circuit are smaller at lower frequencies, we would expect the operating ranges of all of the different circuit parameters to decrease in a similar way. This decrease in operating range of the parameters is closely related to the increased instability of the circuit at lower frequencies. When currents are very small, instabilities due to noise and device imperfections have a greater effect on circuit operation. These instabilities can be avoided by operating the circuit near the middle of its dynamic range. One feature of both the computer simulation and

![Graph showing the relationship between synaptic strength and output voltage](image-url)

**Fig. 5.** Results of the simulation of the model circuit shown in Fig. 4B using NeuralG, a simulation program that shows the levator (LEV) and depressor (DEP) activities for three different values of $I_2$, the synaptic strength of the excitatory synapse from OSC to LEV (Fig. 4B). In this simulation, two different DEP drivers were stimulated, one fast (DEP) and one slow (DEP2). In the three sets of traces, the top trace is the output from LEV, the middle trace is the output from DEP, and the bottom trace is the output from DEP2. Compare with Fig. 1 (Scale bars: 5 sec, 2 volts).
the VLSI circuit is that the transition between output states as \( I_l \) is varied is smooth. In addition, the circuits "fail" gracefully for values of \( I_l \) that are outside the range of normal circuit operation. For values of \( I_l \) which are smaller than \( I_{\text{min}} \) (Fig. 10A), LEV does not receive sufficient excitatory input to allow it to reach its threshold for spiking. It therefore remains silent. Since DEP is not being inhibited by LEV, it continues to spike tonically (in the case of a slow driver DEP) or is silent (in the case of a fast driver DEP). For very large values of \( I_l \), on the other hand, the circuit continues to produce the metathoracic output pattern, since \( w_{1} \) is zero and
the VLSI circuit is that the transition between output states as \( I_r \) is varied is smooth. In addition, the circuits "fail" gracefully for values of \( I_r \) that are outside the range of normal circuit operation. For values of \( I_r \) which are smaller than \( I_{sem} \) (Fig. 10A), LEV does not receive sufficient excitatory input to allow it to reach its threshold for spiking. It therefore remains silent. Since DEP is not being inhibited by LEV, it continues to spike tonically (in the case of a slow driver DEP) or is silent (in the case of a fast driver DEP). For very large values of \( I_r \), on the other hand, the circuit continues to produce the metathoracic output pattern, since \( w_r \) is zero and \( w_2 \) saturates at its maximum value, \( w_2 (\infty) \) (Fig. 10A).

Mathematical Analysis

We developed a simple theoretical analysis of the circuit model shown in Fig. 4B and described above. Note that this analysis is based on an abstraction of the behavior of the simulated circuit. The mathematical details can be found in Appendix A. We computed expressions which describe the behavior of the circuit as \( I_r \) is varied. These expressions express the widths of the bursts of activity of depressor drives before and after a levator burst as functions of \( I_r \) (Fig. 10A). In Fig. 10A, we can see that the width of the depressor burst which precedes a levator burst \( (w_r) \) decreases as \( I_r \) increases, and the width of the depressor burst which follows a levator burst \( (w_r) \) increases as \( I_r \) increases. Different regions of the graph (shaded areas, delimited by asymptotes) correspond to the production of pro-, meso-, and metathoracic rhythmic patterns. For small values of \( I_r \), \( w_r = 0 \) and the depressor activity precedes the
tionships of motor neuron antagonists. The different patterns we observed could be generated by a simple adaptable model circuit, which was both simulated and implemented in VLSI hardware.

**Locomotor Rhythm Generation in Thoracic Segments.** Despite the segmental structure of the insect nervous system, the central pattern generator circuits (CPGS) which underlie rhythmic movements are not necessarily repeated or equivalent in each segment. The locust central pattern generator underlying flight, for example, is distributed in both the meso- and the metathoracic ganglia (Roberson and Pearson, 1983; 1985; Robertson, 1986). Ventilatory rhythms are produced by a dominant central pattern generator in the metathoracic ganglion; indeed, respiratory rhythms recorded in the pro- and mesothoracic ganglia cease when the connectives to the metathoracic ganglion are sectioned (Farley et al., 1967; Miller, 1960, 1966, 1967). That locomotor rhythms could be induced by pilocarpine in the isolated locust pro- and mesothoracic ganglia as well as in the isolated metathoracic ganglion (Rykebusch and Laurent, 1993; this paper) provides evidence that there exist at least partially independent pattern generating circuits for leg movements in each thoracic ganglion or hemiganglion.

Perhaps more surprising is our finding that the phases and frequencies of the evoked rhythms differ in the three thoracic ganglia. These differences in rhythmic patterns may reflect the intrinsic physical differences between the three pairs of insect legs. The front legs are oriented toward the front of the body, whereas the hind legs are oriented toward the rear. This implies that the intrinsic locomotor rhythms for these legs must differ, as the sequence of levator and depressor activity (protraction and retraction) would be different during a step. Cruse (1976) has found that the three pairs of legs in stick insects have different functions during walking and the maintenance of posture. During horizontal walking, the foreleg has primarily a feeler function, while the middle leg has a supportive function and the hind leg has both supportive and propulsive functions. These roles can change, however, if the insect walks on a non-horizontal surface, which implies that individual segmental oscillators, already tuned in a segment-specific manner, in addition must have the capability of adapting their output to the changing functional role of the limb which they move.

**Behavioral experiments** that, during tethered walking, the insect hind leg can exhibit either 1:1 or 1:2 coupling with the front and middle legs; i.e., the front and middle legs occasionally make two steps for one step of the hind leg (N. Hatipoulos, personal communication; Graham 1978a, b). Since the hind leg is longer than the front or middle legs, it compensates for a missed step by making a larger amplitude step at the next cycle. That the step frequencies of the hind leg are lower than those of the front and middle legs in walking animals is consistent with the finding that locomotor patterns recorded from isolated metathoracic ganglia are slower than those produced by the pro- and mesothoracic ganglia. Several models of insect walking have in fact proposed a anterior-posterior gradient of frequencies for the thoracic segments, with the hind segment having the lowest intrinsic frequency (Wilson, 1966; Graham, 1977; reviewed in Graham, 1985). Such a frequency gradient appears to be necessary to produce appropriate phase lags and coupling between the legs, and can also explain the occasional absence of rear leg protraction.

Since we have established that the phase relationships between trochanteral antagonists are tuned in a segment-specific manner, it would be interesting to compare the patterns of activity of the other motor neuron pools, such as the tibial and tarsal motor neurons, to the corresponding metathoracic patterns (Rykebusch and Laurent, 1993). Clearly there is also a need to relate the segmental differences between rhythmic motor patterns to the actual movements of the legs during walking. At this time, however, no detailed study...
levator activity. This corresponds to the prothoracic rhythm. For intermediate values of \( I_I \), both \( w_{1} \) and \( w_{2} \) are greater than zero, and the depressor activity both precedes and follows a levator burst. This corresponds to the mesothoracic hyperactivity. For large values of \( I_I \), \( w_{1} = 0 \) and the depressor activity follows the levator activity. This corresponds to the metathoracic rhythm.

In Fig. 10B, we show measured values of \( w_{1} \) and \( w_{2} \) from the output of the integrated circuit as \( I_I \) is varied. The solid lines are fits of the forms given by the theoretical expressions for \( w_{1} \) and \( w_{2} \) (see Appendix A). Because \( I_I \) is controlled by a voltage, exact values of the current \( I_I \) could not be determined. The absissa (ordinate) represents a normalized current. Note that the graph for \( w_{1} \), in Fig. 10B would intersect the \( w_{2} \) axis at large enough values of \( I_I \), but that a portion of the graph was truncated to expand the most interesting region of the graph, for small values of \( I_I \).

**Discussion**

We have shown that pilocarpine induces rhythmic activity in leg motor neurons of isolated locust pro-, meso-, and metathoracic ganglia. The patterns recorded in the three ganglia differed in their sensitivities to pilocarpine, their frequencies, and the phase relationships of motor neuron antagonists. The different patterns observed could be generated by a simple adaptable model circuit, which was both simulated and implemented in VLSI hardware.

**Locomotor Rhythm Generation in Thoracic Segments.**

Despite the segmental structure of the insect nervous system, the central pattern generator circuits (CPGs) which underlie rhythmic movements are not necessarily repeated or equivalent in each segment. The locust central pattern generator underlying flight, for example, is distributed in both the meso- and the metathoracic ganglia (Robinson and Pearson, 1983; 1985; Robertson, 1986). Ventilatory rhythms are produced by a dominant central pattern generator in the metathoracic ganglion; indeed, respiratory rhythms recorded in the pro- and mesothoracic ganglia cease when the connectives to the metathoracic ganglion are sectioned (Farley et al., 1967; Miller, 1960, 1966, 1967). That locomotor rhythms could be induced by pilocarpine in the isolated locust pro- and mesothoracic ganglia as well as in the isolated metathoracic ganglion (Rycbebusch and Laurent, 1993; this paper) provides evidence that there exist at least partially independent pattern generating circuits for leg movements in each thoracic ganglion or hemiganglion.

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Differences in intrinsic frequencies of the segmental rhythms might also be related to the morphological differences of the limbs. It has been observed in behavioral experiments that, during tethered walking, the insect hind leg can exhibit either 1:1 or 1:2 coupling with the front and middle legs; i.e., the front and middle legs occasionally make two steps for one step of the hind leg (N. Hatzopoulos, personal communication; Graham 1978b, a). Since the hind leg is longer than the front or middle legs, it compensates for a missed step by making a larger amplitude step at the next cycle. Thus the step frequencies of the hind leg are lower than those of the front and middle legs in walking; animals is consistent with the finding that locomotor patterns recorded from isolated metathoracic ganglia are slower than those produced by the pro- and mesothoracic ganglia. Several models of insect walking have in fact proposed a anterior-posterior gradient of frequencies for the thoracic segments, with the hind segment having the lowest intrinsic frequency (Wilson, 1966; Graham, 1977; reviewed in Graham, 1985). Such a frequency gradient appears to be necessary to produce appropriate phase lags and coupling between the legs, and can also explain the occasional absence of rear leg protraction.

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**Fig. 9.** Range of the synaptic current \( I_{I} \) as a function of the period. The range of \( I_{I} \) is defined as the difference in synaptic current required to switch the circuit from a "prothoracic" rhythm (\( w_{2} \)) to a "mesothoracic" rhythm (\( w_{1} \)). Since the synaptic current in the chip could not be measured, values of the currents were estimated from voltage measurements and normalized. The range was determined for five different time scales, represented on the abscissa as the period. Note that both the current range and the period are plotted on log scales. Thus the circuit is more stable at higher frequencies of operation (smaller periods) can be attributed to the larger ranges over which parameters can be modulated at these frequencies.

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**Fig. 10.** Comparison of chip performance and theoretical analysis. A. Graph of theoretical expressions for \( w_{1} \) and \( w_{2} \) (see Appendix A) as a function of the magnitude of \( I_{I} \), the excitation current from OSC to the levator motor pool driver (Fig. 2). Solutions lie within the shaded rectangle delimited by the asymptotic \( w_{1}(\infty) \) and the instantaneous \( w_{1}(t) \). See Results and Appendix B for details. B. Measured values of \( w_{1} \) and \( w_{2} \) from integrated circuit output, as a function of the current \( I_{I} \). Solid lines are fits of the form given by the theoretical expressions derived in Appendix A, and plotted in A. Because \( I_{I} \) was modified by changing a voltage on the integrated circuit, exact current values could not be determined. The current on the abscissa is therefore a normalized current.
Rhythmic Locomotor Patterns

Comparing the patterns of activities of the different leg muscles during walking has been done. Accordingly, it is unclear how the differences in phase relationships of motor neuron activity in different segments might be related to the different functional roles of the legs during walking.

Serial Homology of Walking Circuits. During embryogenesis, the six thoracic hemiganglia of the locust nervous system each arise from 30 neuroblasts that are organized according to the same fundamental plan and undergo similar developmental processes (Bate, 1976). Furthermore, other anatomical studies have shown that with a few exceptions, serially homologous motor neurons in the thoracic ganglia are morphologically indistinguishable (Wilson, 1979a). Paired intracellular recordings of leg motor neurons have revealed some differences between the patterns of connections of motor neurons in the thoracic ganglia compared to pro- or mesothoracic ganglia, however. In particular, connections between motor neurons were found to exist only in the metathoracic ganglion and not in the pro- or mesothoracic ganglia (Wilson, 1979b). The nature of these connections, however, indicates that this difference is likely to be related to the specialization of the hind legs for jumping and may not be functionally relevant during walking. Similarly, it appears that other major populations of neurons in the thoracic ganglia—namely, the nonspiking and spiking local interneurons—are also serially homologous and make similar connections within each hemiganglion (Burrus, 1992). Burrus and Watkins (1996). Based on these results, it seems reasonable to assume that the locomotor circuits in segmentally homologous thoracic ganglia are very similar, despite the different rhythmic output patterns they generate. Such was the assumption made here in designing a model circuit.

Mechanisms Underlying Pattern Generation. The neural mechanisms by which the central pattern generator of the locust is able to generate the rhythmic motor patterns it produces are complex and not yet fully understood. However, it is clear that the central pattern generator is a crucial component of the locomotor system, and its activity is essential for the production of normal locomotion. The central pattern generator is a network of neurons that are rhythmically active and are responsible for generating the rhythmic motor patterns observed in the locomotor system. The central pattern generator is formed by a group of neurons that are rhythmically active and are responsible for generating the rhythmic motor patterns observed in the locomotor system. The central pattern generator is formed by a group of neurons that are rhythmically active and are responsible for generating the rhythmic motor patterns observed in the locomotor system. The central pattern generator is formed by a group of neurons that are rhythmically active and are responsible for generating the rhythmic motor patterns observed in the locomotor system. The central pattern generator is formed by a group of neurons that are rhythmically active and are responsible for generating the rhythmic motor patterns observed in the locomotor system. The central pattern generator is formed by a group of neurons that are rhythmically active and are responsible for generating the rhythmic motor patterns observed in the locomotor system. The central pattern generator is formed by a group of neurons that are rhythmically active and are responsible for generating the rhythmic motor patterns observed in the locomotor system. The central pattern generator is formed by a group of neurons that are rhythmically active and are responsible for generating the rhythmic motor patterns observed in the locomotor system. The central pattern generator is formed by a group of neurons that are rhythmically active and are responsible for generating the rhythmic motor patterns observed in the locomotor system. The central pattern generator is formed by a group of neurons that are rhythmically active and are responsible for generating the rhythmic motor patterns observed in the locomotor system. The central pattern generator is formed by a group of neurons that are rhythmically active and are responsible for generating the rhythmic motor patterns observed in the locomotor system. The central pattern generator is formed by a group of neurons that are rhythmically active and are responsible for generating the rhythmic motor patterns observed in the locomotor system. The central pattern generator is formed by a group of neurons that are rhythmically active and are responsible for generating the rhythmic motor patterns observed in the locomotor system. The central pattern generator is formed by a group of neurons that are rhythmically active and are responsible for generating the rhythmic motor patterns observed in the locomotor system. The central pattern generator is formed by a group of neurons that are rhythmically active and are responsible for generating the rhythmic motor patterns observed in the locomotor system. The central pattern generator is formed by a group of neurons that are rhythmically active and are responsible for generating the rhythmic motor patterns observed in the locomotor system. The central pattern generator is formed by a group of neurons that are rhythmically active and are responsible for generating the rhythmic motor patterns observed in the locomotor system. The central pattern generator is formed by a group of neurons that are rhythmically active and are responsible for generating the rhythmic motor patterns observed in the locomotor system. The central pattern generator is formed by a group of neurons that are rhythmically active and are responsible for generating the rhythmic motor patterns observed in the locomotor system. The central pattern generator is formed by a group of neurons that are rhythmically active and are responsible for generating the rhythmic motor patterns observed in the locomotor system. The central pattern generator is formed by a group of neurons that are rhythmically active and are responsibly
Lymnaea stagnalis (Benjamin and Elliott, 1989) uses mechanisms similar to those employed by our model circuit. The Slow Oscillator (SO) of the mollusc plays a role much like that of OSC in our model circuit. SO initiates, maintains, and controls the frequency of the small oscillations; its input signal is a slow depolarizing input. SO is the primary source of excitatory drive to a small network of interneurons forming the central pattern generator, which in turn provides the drive to a set of baccal motor neurons. The interneurons (N1, N2, and N3) which form the core of the central pattern generator produce rhythmic output as a result of their intrinsic properties (e.g., endogenous bursting, postinhibitory rebound, plateau potentials) as well as their synaptic connections. N1 and N2 form a network reminiscent of the design of our two-neuron “bursting” neuron, with slow excitation from N1 to N2 and delayed inhibition from N2 to N1. N3 is first inhibited by N1, and then produces a postinhibitory burst of action potentials, which is similar to the LEV-DEP interaction in our model network.

The ability to generate rhythmic bursts of activity can be a feature of a single neuron (Alving, 1968), or can result from the synaptic interactions of several neurons (Getting and Dekin, 1985). Although intrinsically bursting neurons have yet to be identified in locusts, a small circuit of two neurons in the flight system of the locust (301 and 501) have all the properties necessary to generate sustained alternating rhythmic activity (Robertson and Pearson, 1985). In fact, the connections found between the 301 and 501 neurons are remarkably similar to the connections between cell 1 and cell 2 in our model bursting neuron circuit (Fig. 4A).

In the model we devised, the output pattern could be switched between the characteristic of the presos- and the presos- and metathoracic ganglia by modifying a single synaptic coupling parameter in the circuit. There are now numerous examples of biological pattern generating circuits which can produce several rhythmic patterns: the pyloric and gastric motor patterns in the stomatogastric system of crabs (Weinmann et al., 1991); withdrawal and swimming in Triboniops (Gerritsen, 1985); forward and backward scaphognathite beating in crabs (Simmers and Bush, 1983); jumping and kicking in the locust (Gymber and Pearson, 1989), to name just a few. In some of these systems, the switch from one pattern to another is accomplished under the action of a neuromodulator which alters cellular and synaptic properties of the circuit elements. For example, the crustacean gastric mill motor pattern can be switched from “squeezing” to “cut-and-grind” mode under the action of the peptide proctolin (Beirne and Selverston, 1988; Beirne, 1988).

Design of Realistic Walking Robots

It is important that our model circuit be designed not only to produce a range of output behaviors, but also to be as realistic as possible. In this section, we will discuss some of the key features that we believe are necessary for a realistic model of walking.

Appendix A

Mathematical Description of the Levator-Depressor Model

In this appendix, we derive the expressions for the widths of the depressor bursts \( \psi \) and \( \psi' \) as a function of the synaptic parameter \( I \). The circuit diagram is shown in Fig. 4B, and a schematic diagram of the relative timing of OSC, LEV, and DEP outputs is shown in Fig. 4C. Graphs of \( \psi \) and \( \psi' \) are plotted as a function of \( I \) in Fig. 10A.

Variables

\( \psi \): Capacitance of neurons
\( \psi' \): Neuron spike threshold
\( \psi' \): Magnitude of excitatory synaptic current from OSC to LEV
\( \psi' \): Magnitude of excitatory synaptic current from OSC to DEP
\( \psi' \): Magnitude of inhibitory synaptic current from LEV to DEP

Acknowledgments

Supported by grants from NIH and ONR to GL. GL is a Sloan and McKnight scholar. SR was supported by fellowships from AT&T and ONR, and an NIH Training Grant. MW was supported by an ONR fellowship. We thank Dr. Ari Berkowitz, Dr. Nicho Hatasopulos and Christine Chee-Ruiter for their thoughtful comments on previous drafts of this manuscript; Drs. Lloyd Watts and Nicho Hatasopulos for useful discussions; and two anonymous reviewers for their helpful suggestions. We are particularly indebted to Dr. Lloyd Watts for incorporating many useful features into Spike and NeuralLog during the course of this work, and to Dr. Carver Mead for providing support and laboratory space.

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\[ I = \frac{C_{V_2}}{W_{osc} + \tau_2 - W_{lev}} - \frac{C_{V_2}}{L_2 - \tau_2} \] (8)

Note that only the first two terms in (8) are positive. In other words, \( \omega > 0 \) provided that either \( W_{osc} \) or \( \tau_2 \) (or both) are sufficiently large. \( \tau_2 \) is large means that the excitative drive to DEP has a slow time constant of decay.

**Constraints**

For this circuit to operate in the desired range, the current \( I \) must satisfy the following constraint, represented graphically in Fig. 10A by a vertical dashed line:

\[ I > I_{osc} = \frac{C_{V_2}}{W_{osc}} \] (9)

This constraint expresses the requirement that the time needed for LEV to charge its membrane to threshold must be less than \( W_{osc} \), the duration of the OSC burst. If \( I < I_{osc} \), LEV will remain silent, and DEP will receive excitative input from OSC but no inhibition from LEV.

**Asymptotes**

For large values of \( I_1 \) and \( I_2 \) and \( w_2 \) will asymptotically approach the following limits:

\[ w_2(\infty) = \frac{C_{V_2}}{W_{osc} + \tau_2 - W_{lev}} - \frac{C_{V_2}}{L_2 - \tau_2} \] (10)

\[ \lim_{w_2 \to \infty} w_1 = -\frac{C_{V_2}}{L_2} \] (11)

Since \( w_1 \) cannot be negative, the negative value of the asymptote given in (11) means that \( w_1 \) will go to zero when \( I_2 = I_2 \) and will stay at zero as \( I_2 \) is increased further.

**Solutions of Interest**

1. Prothoracic solution \((w_2 = 0)\)

From equation (8), \( w_2 = 0 \) when:

\[ I = \frac{C_{V_2}}{W_{osc} + \tau_2 - W_{lev}} - \frac{C_{V_2}}{L_2} \] (12)

If \( I_2 \) is large enough, \( w_2 \) can be rewritten simply as:

\[ I = \frac{C_{V_2}}{W_{osc} + \tau_2 - W_{lev}} - \frac{C_{V_2}}{L_2} \] (13)

It follows from (13) that the prothoracic output pattern occurs when:

\[ I_{osc} < I < \frac{C_{V_2}}{W_{osc} + \tau_2 - W_{lev}} \] (14)

Combining (3) and (14), it follows that this solution only exists when \( W_{osc} < L_2 \), i.e., if the duration of a LEV burst is longer than the duration of the excitative synaptic current from OSC to DEP.

2. Metathoracic solution

The metathoracic solution occurs when both \( W_{osc} \) and \( I_2 \) are nonzero. From (5) and (13), we obtain the following range for \( I_2 \):

\[ \frac{C_{V_2}}{W_{osc} + \tau_2 - W_{lev}} < I_2 < I_2 \] (15)

Within this range, \( w_2 > 0 \) when:

\[ C_{V_2} + W_{osc} + \tau_2 - W_{lev} > \frac{2C_{V_2}}{w_2} \] (16)

And \( w_2 < 0 \) when:

\[ \frac{2C_{V_2}}{w_2} - \frac{C_{V_2}}{W_{osc} + \tau_2 - W_{lev}} > I_2 \] (17)

3. Metathoracic solution \((w_1 = 0)\)

It follows from (5) that the metathoracic output pattern will occur when \( I_1 \geq I_2 \).

**References**

\begin{equation}
I_1 = \frac{CV_T}{W_{OSC} + \tau_d - W_{LEV}} \quad I_d
\end{equation}

It follows from (13) that the prothoracic output pattern occurs when:

\begin{equation}
I_{dmax} < I_d < \frac{CV_T}{W_{OSC} + \tau_d - W_{LEV}}
\end{equation}

Combining (3) and (14), it follows that this solution only exists when \( W_{LEV} > \tau_d \) (i.e., if the duration of a LEV burst is longer than the duration of the excitatory synaptic current from OSC to DEP).

2. Metathoracic solution

The mesothoracic solution occurs when both \( w_1 \) and \( w_2 \) are nonzero. From (5) and (13), we obtain the following range for \( I_1 \):

\begin{equation}
\frac{CV_T}{W_{OSC} + \tau_d - W_{LEV}} < I_1 < I_{dmax}
\end{equation}

Within this range, \( w_1 > 0 \) and when:

\begin{equation}
\frac{2CV_T}{W_{OSC} + \tau_d - W_{LEV}} < I_1 < \frac{CV_T}{W_{OSC} + \tau_d - W_{LEV}}
\end{equation}

And when \( w_2 > 0 \) when:

\begin{equation}
\frac{2CV_T}{W_{OSC} + \tau_d - W_{LEV}} < I_1 < \frac{CV_T}{W_{OSC} + \tau_d - W_{LEV}}
\end{equation}

3. Metathoracic solution \((w_1 = 0)\)

It follows from (5) that the metathoracic output pattern will occur when \( I_1 \geq I_{dmax} \).

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