

Postural Control in the Lamprey: A Study With a Neuro-Mechanical Model

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Postural control in the lamprey: a study with a neuro-mechanical model. *J Neurophysiol* 84: 2880–2887, 2000. The swimming lamprey normally maintains the dorsal-side-up orientation due to activity of the postural control system driven by vestibular organs. Commands for postural corrections are transmitted from the brain stem to the spinal cord mainly by the reticulospinal (RS) pathways. As shown in previous studies, RS neurons are activated by contralateral roll tilt, they exhibit a strong dynamic response, but much weaker static response. Here we test a hypothesis that decoding of these commands in the spinal cord is based on the subtraction of signals in the left and right RS pathways. In this study, we used a neuro-mechanical model. An intact lamprey was mounted on a platform that restrained its postural activity but allowed lateral locomotor undulations to occur. The activity in the left and right RS pathways was recorded by implanted electrodes. These natural biological signals were then used to control an electrical motor rotating the animal around its longitudinal axis toward the stronger signal. It was found that this “hybrid” system automatically stabilized a normal orientation of the lamprey in the gravitational field. The system compensated for large postural disturbances (lateral tilt up to $\pm 180^\circ$) due to wide angular zones of the gravitational sensitivity of RS neurons. In the nonswimming lamprey, activity of RS neurons and their vestibular responses were considerably reduced, and the system was not able to stabilize the normal orientation. However, the balance could be restored by imposing small oscillations on the lamprey, which elicited additional activation of the vestibular organs. This finding indicates that head oscillations caused by locomotor movements may contribute to postural stabilization. In addition to postural stabilization, the neuro-mechanical model reproduced a number of postural effects characteristic of the lamprey: 1) unilateral eye illumination elicited a lateral tilt (“dorsal light response”) due to a shift of the equilibrium point in the vestibular-driven postural network; 2) removal of one labyrinth resulted in a loss of postural control due to an induced left-right asymmetry in the vestibulo-reticulospinal reflexes, which 3) could be compensated for by asymmetrical visual input. The main conclusion of the present study is that natural supraspinal commands for postural corrections in the roll plane can be effectively decoded on the basis of subtraction of the effects of signals delivered by the left and right RS pathways. Possible mechanisms for this transformation are discussed.

INTRODUCTION

The lamprey (cyclostome) is normally oriented with its dorsal side up during swimming (Fig. 1A). Any deviation from this orientation (roll tilt α) evokes a corrective motor response

aimed at restoring normal orientation. This response may include lateral flexion of the ventrally deviated tail, lateral deviation of the dorsal fin, and body twisting (Ullén et al. 1995a). These movements all generate a torque rotating the lamprey around its longitudinal axis in a direction opposite to the initial tilt (white arrow in Fig. 1A).

Postural corrective reflexes in the lamprey are driven by vestibular input. After a unilateral or bilateral labyrinthectomy, the lamprey is not able to maintain a particular orientation in space (Deliagina 1997a; Ullén et al. 1995a). In contrast to vestibular input, visual input exerts only a modulatory effect on the postural orientation; it elicits a lateral tilt toward the more illuminated eye (dorsal light response) (Ullén et al. 1995b).

As in other vertebrates, the basic neural mechanisms for postural control in the lamprey are located in the brain stem and spinal cord. The brain stem processes and integrates vestibular and visual signals and then sends commands to the spinal cord. Under the effect of these signals, spinal mechanisms then generate corrective motor responses. Commands for postural corrections can be transmitted via the reticulospinal (RS), vestibulospinal, and propriospinal pathways (Rouse and McClellan 1997; Rovainen 1979); of these, the RS pathways have been suggested to be the most important (Deliagina et al. 1993). The two bilaterally symmetrical RS pathways originate from the neurons of four reticular nuclei of the brain stem and reach even the most caudal spinal segments (Busièrés 1994; Nieuwenhuys 1972; Ohta and Grillner 1989; Rovainen 1979). Vestibular and visual inputs to RS neurons were initially studied in the experiments on the brain stem isolated with vestibular organs and eyes. It was found that the majority of RS neurons receive excitatory input from the contralateral labyrinth and become activated with contralateral roll tilt (Deliagina et al. 1992a,b; Orlovsky et al. 1992). They also receive visual input and become activated with illumination of the ipsilateral eye but inhibited with illumination of the contralateral eye (Deliagina et al. 1993). These data about sensory inputs to RS neurons and the output signals sent to the spinal cord were used to formulate a conceptual model of the roll control system (Fig. 1B) (Deliagina 1997a; Deliagina et al. 1993).

On reaching the spinal cord, the RS commands affect different types of neurons (Ohta and Grillner 1989) and cause

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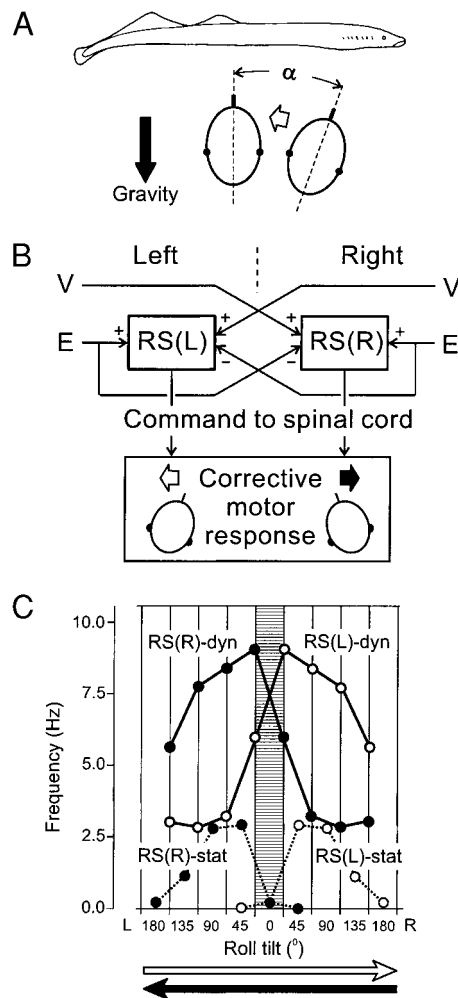


FIG. 1. Postural orientation in the swimming lamprey, principal elements of the postural network, and vestibular responses in reticulospinal (RS) neurons. **A:** the lamprey is normally oriented with its dorsal side up, and any deviation from this orientation (roll tilt, α) evokes a set of corrective motor responses aimed at restoration of the normal orientation. **B:** conceptual model of the roll control system (based on Deliagina 1997a; Deliagina et al. 1993). Vestibular (V) and visual (E) inputs to RS neurons have been experimentally established. Decoding of RS commands is supposed to be based on the subtraction of the effects produced by the signals in the left and right RS pathways. **C:** responses of *group 1* RS neurons in intact lamprey to roll tilt (based on Deliagina and Fagerstedt 2000). Neurons were tested by a stepwise 45° tilt applied at different initial orientations of the animal (left or right roll up to 180°). The response consisted of 2 components: dynamic (activity during tilt) and static (activity at the sustained new position). The mean value of these components [averaged over a population of RS neurons on the 2 sides, RS(R) and RS(L)] is plotted against the initial orientation. Arrows below the graph show the direction of rotation necessary for activation of RS(R) (black arrow) and RS(L) (white arrow).

numerous changes in the locomotor efferent pattern generated by the spinal cord (Wannier et al. 1998). It remains unknown, however, what effect these changes have on postural orientation. In other words, a transfer function between the RS pathways transmitting commands for postural corrections and the spinal motor network output has not been defined. When formulating the model of the roll control system, a hypothesis was advanced that each of two RS pathways (left and right) causes an ipsilateral roll tilt of the lamprey, and the resulting corrective motor response is proportional to the difference between the signals delivered by the left and right pathways

(Fig. 1B). This hypothesis reflects the idea of Magnus (1924) that postural orientation results from the interaction of opposing postural reflexes.

In the present study we have tested this model of the roll control system. This was possible due to the recent methodological developments. First, a technique has been developed for recording the activity of larger RS axons in intact lampreys by means of implanted electrodes (Deliagina and Fagerstedt 2000; Deliagina et al. 2000b). With this technique, responses to roll tilt in RS neurons were characterized. Two groups of RS neurons could be distinguished; each group is rather homogeneous. In *group 1*, tilting the animal elicited a response that consisted of two components: a dynamic component (activity during tilt), and a static component (activity in a sustained new position), the dynamic component being much stronger than the static one (Fig. 1C). The responses in the left and right subgroups had their peaks around 90° of the contralateral tilt; the zones of activity of the two subgroups partly overlap around 0° . *Group 1* neurons receive also visual input, and become activated with illumination of the ipsilateral eye. In contrast to *group 1*, the RS neurons of *group 2* become activated with tilt in any direction, and with illumination of any eye. It was suggested that *group 1* is involved in postural control (Deliagina and Fagerstedt 2000).

Second, a technique was devised for examining the role of specific neuron groups in postural control (Deliagina et al. 1998). With this technique, the activity of a group of neurons under study was used to drive an electromechanical system ("robot") producing postural corrections. In these experiments, the robot was driven by the motoneurons that normally control the effector organ. In the present study, this novel technique was further elaborated, and the robot was driven by the commands generated in the brain and addressed to the spinal cord. We deprived the intact lamprey of the ability to change orientation by itself and used the spikes, generated by *group 1* RS neurons and recorded by implanted electrodes from the left and right RS pathways, to control an electromechanical system that rotated the animal (see METHODS and Fig. 2A). The direction of rotation was determined by the prevailing (left or right) signal, as was suggested by the initial model (Fig. 1B). We analyzed the system under two conditions: 1) with an open loop, we recorded the vestibulo-reticulospinal responses to roll tilt; 2) with a closed loop, when the electromechanical system was stabilizing the lamprey's orientation in the gravitational field, we examined dynamic characteristics of the system and related changes in the activity of RS neurons. It has been found that the closed-loop system not only effectively stabilizes the animal's orientation in space but also reproduces a number of other postural effects characteristic for the lamprey. These observations strongly support the validity of the model presented in Fig. 1B.

A brief account of this study has been published in abstract form (Zelenin et al. 1998).

METHODS

Experiments were carried out on adult lamprey *Lampetra fluviatilis* ($n = 21$) at a temperature of 7°C . Activity of larger RS axons was recorded bilaterally by chronically implanted extracellular electrodes. This method was described in detail in the previous paper (Deliagina et al. 2000b). In short, the electrodes were made of silver wire ($75\ \mu\text{m}$

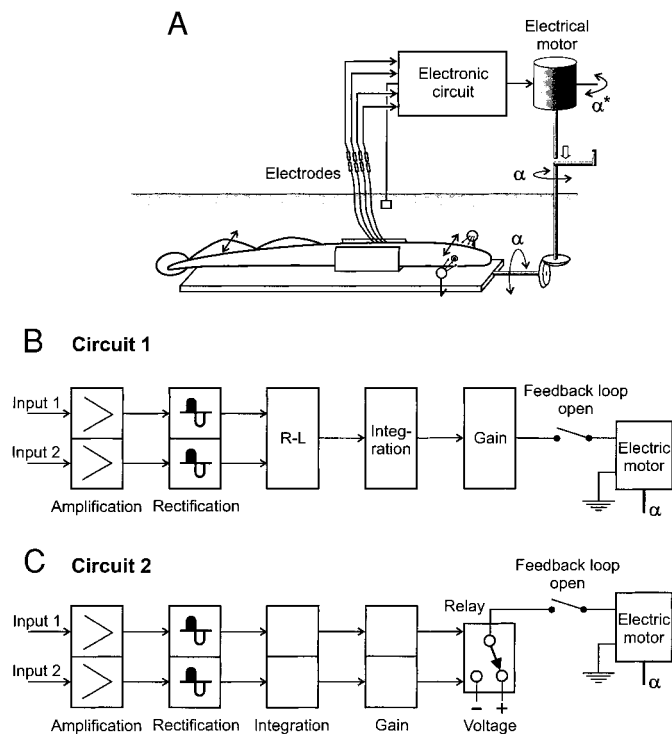


FIG. 2. Experimental arrangement. **A**: setup for rotating the lamprey. The animal was mounted on a platform. In locomoting animals, the mid-body area was attached to the platform, whereas the anterior and posterior parts could perform locomotor undulations (shown by bilateral arrows). In nonlocomoting animals, movements of the whole body were restrained. The platform could be rotated in the roll plane (α) either manually by the handle or by the electric motor. The motor was controlled by the signals from the implanted electrodes after their processing in the electronic circuit. Small periodical oscillations (α^*) could be introduced into the system by manually rotating the stator of the electric motor. Each of the eyes could be illuminated separately by the fiber optic system. **B** and **C**: 2 versions of the electronic circuit for processing signals from the implanted electrodes (see text in METHODS for further details).

diam, 3 mm in length) and glued to a plastic plate ($6 \times 2 \times 0.2$ mm). Similar wires on the opposite side of the plate allowed bipolar recording, which led to a reduction of artifacts caused by electrical activity of surrounding muscles during swimming. Additional means to reduce the electromyographic (EMG) artifacts were 1) denervation of surrounding myotomes by bilaterally cutting the spinal roots (± 5 segments); and 2) wrapping the electrode plate together with adjoining spinal segments in a strip of thin ($20 \mu\text{m}$) plastic film. The electrodes were implanted under MS-222 anesthesia, at the level of the last gill. To record separately from the left and right RS pathways, a longitudinal split of the spinal cord (5 mm in length) was performed, and an isolating plastic wall (attached to the electrode plate) was positioned in the split. As shown in the previous studies, these electrodes recorded almost exclusively the action potentials in larger RS axons, which have conduction velocities of 2–5 m/s (Deliagina and Fagerstedt 2000; Deliagina et al. 2000a). With a distance between the electrodes equal ~ 1 mm, they occurred disposed over the lateral parts of the spinal cord where the *group 1* RS axons are located (Deliagina and Fagerstedt 2000).

The experiments were performed both on animals exhibiting locomotor-like activity and on quiescent animals. In both cases, the lamprey was mounted on a platform. In experiments on locomoting animals, a part of the body ($\sim 20\%$ in length), including denervated segments, was gently fixed between the two plates of a holder (Fig. 2A). This part was thus immobilized, whereas the anterior and posterior body parts could move. Locomotor-like activity appeared either spontaneously or in response to tactile stimulation. During this activ-

ity, the anterior and posterior parts of the body performed periodical lateral undulations characteristic of swimming (bilateral arrows in Fig. 2A). In experiments on nonswimming lampreys, any movements were restrained not only in the mid-body area, but also in its rostral and caudal parts. In these experiments, either of the eyes could be illuminated by fiber optic systems (90 W).

Because of the fixation on the platform, the lamprey was not able to produce a roll tilt by itself, but the tilt (α) could be easily imposed from without by rotating the platform. This was performed either manually (open-loop conditions) or by the electrical motor controlled by the activity of RS neurons (closed-loop conditions). When the closed-loop system was functioning, small periodic oscillations (α^* , Fig. 2A) could be introduced into the system by manually rotating the stator of the electrical motor.

Two different designs of the electronic circuit for processing neural signals were used. In *circuit 1* (Fig. 2B), spike waveforms from the two bipolar electrodes (right, *input 1*, and left, *input 2*) were amplified (the amplification could be regulated separately in each channel) and rectified. Then their difference (R-L) was obtained and subjected to integration. This integrated signal was amplified (gain) and used to drive a low-inertia DC motor that produced rotation of the lamprey. The rotation was directed toward the stronger signal as suggested by the model (Fig. 1B), and the angular speed (up to $100^\circ/\text{s}$) was proportional to the value of the signal. The integrator had a “leakage” time constant of 1–5 s, and the speed of rotation decayed correspondingly. Integration of signals can be considered as a reflection of the inertial properties of the lamprey’s body; the motor commands have to act for some time to produce a certain motor effect. A decay of the angular speed after termination of the motor command can be considered as the effect of viscosity of the surrounding medium. An estimate of these mechanical characteristics of the lamprey’s body was done by Ekeberg and Grillner (1999) and Kozlov et al. (1999).

Circuit 2 (Fig. 2C) was designed to produce an oscillatory mode of operation of the postural system (Deliagina et al. 1998). As in *circuit 1*, spike waveforms from the two electrodes were amplified (the amplification could be regulated separately in each channel) and rectified. Then they were integrated separately (leakage time constant, 100–200 ms), amplified and used to control a bi-stable relay. Such a processing of signals allowed us to transform even individual spikes into pulses that were long enough to switch the relay. A function of the relay was to switch a polarity of the voltage applied to the electrical motor and thus to reverse its direction of rotation in accordance with the prevailing input signal. The absolute value of the speed of rotation did not depend on the value of input signals and could be established manually (from 5 to $100^\circ/\text{s}$) by adjusting an applied voltage. Because of a very short leakage time constant, the process of integration of the input signal was rapidly terminated, and therefore *circuit 2* did not simulate the inertial properties of the body. After switching the relay, the speed remained constant until the next switch. Thus *circuit 2* did not simulate the effect of the viscosity of water on the moving lamprey. The system with *circuit 2* was always in motion, and the role of RS signals was only to change the direction of rotation.

RESULTS

Stabilization of normal posture

Responses of RS neurons to trapezoid roll tilts under open-loop conditions were recorded in 21 experiments. Usually, from 1 to 4–5 *group 1* neurons were recorded by each electrode. The responses are illustrated in Fig. 3 for the lamprey in a quiescent state (**A**), and when exhibiting locomotor-like activity (**B**). Typically, the neurons were excited with contralateral tilt, whereas responses to ipsilateral tilt were weaker and much less frequent (see also Fig. 1C) (Deliagina and Fagerstedt 2000; Deliagina et al. 2000b). They exhibited strong activation

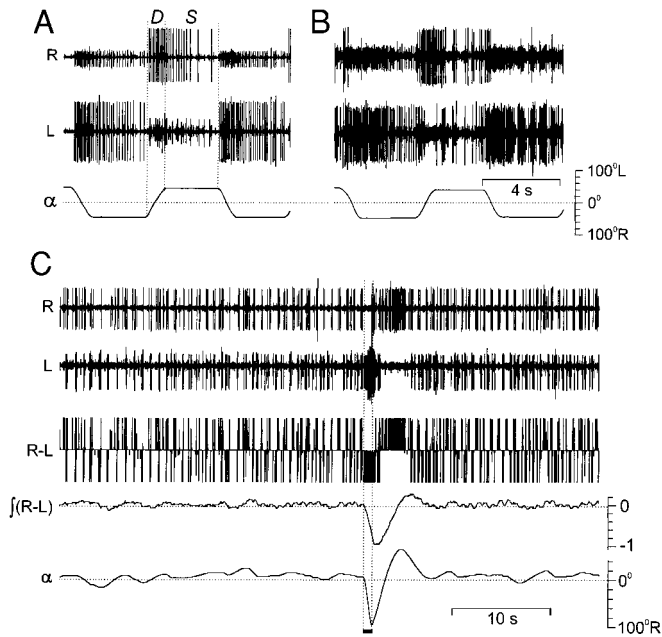


FIG. 3. Activity of axons of group 1 RS neurons on the right (R) and left (L) side under different conditions. *A* and *B*: open-loop conditions. Responses to roll tilts were recorded initially in the nonswimming lamprey (*A*) and then during the locomotor-like activity (*B*) (modified from Deliagina and Fagerstedt 2000). Locomotor rhythm is reflected in a periodic modulation of RS neurons. *C*: closed-loop conditions (*circuit 1*), swimming lamprey. Stabilization of the dorsal-side-up orientation. A horizontal bar indicates the period when the loop was opened, and a 90° tilt was produced by the experimenter. In *C*, in addition to input signals, a difference between the rectified spike waveforms in the 2 channels, right and left (R-L) is shown as well as its integrated value, $f(R-L)$ (arbitrary units).

during a movement (dynamic response, *D*), and much smaller and gradually decaying activity at a new, sustained position (static response, *S*). Both responses were more pronounced during swimming.

In the experiments on swimming animals ($n = 4$), *circuit 1* (see METHODS and Fig. 2*B*) was used for processing nervous signals. After closing the feedback loop, we gradually increased the gain until the system started to operate normally. This was manifested by a maintenance of the lamprey in a certain orientation. If this orientation differed from the normal one (dorsal side up), we increased the amplification of the “weaker” signal to reach the normal orientation. The system was able to compensate for any postural disturbances. This is illustrated in Fig. 3*C*, where a 90° roll tilt was performed by the experimenter under transient open-loop conditions (marked by a bar). This tilt evoked activation of the contralateral RS neurons and was compensated for rapidly after the loop had been closed again. In some cases, as in Fig. 3*C*, a temporal overcompensation was observed.

Stabilization of the normal orientation was observed in all experiments on swimming lampreys. Examination of the effect of regulated parameters (gain and leakage time constant) on postural stabilization was hampered in these experiments, however, because of the considerable variability of locomotor activity in restrained animals, and corresponding variability in the activity of RS neurons and in their vestibular responses (see also Deliagina et al. 2000b). Nevertheless, it was evident that a value of the leakage time constant, when changed from 1 to 5 s, was not critical for the stabilization to occur.

In nonswimming animals, vestibular responses in RS neurons are much less variable (Deliagina and Fagerstedt 2000; Deliagina et al. 2000b). However, when *circuit 1* was used in nonswimming lampreys (11 tests in 5 animals), stabilization of the body orientation occurred only occasionally (Fig. 4*A*); more often, the system was not able to maintain any particular body orientation or to compensate for postural disturbances even with increased gain in the circuit (Fig. 4*B*). The reason for this failure was the smaller value of vestibular responses in RS neurons in the nonswimming lampreys compared with the swimming ones, and especially a considerable reduction (Fig. 3, *A* and *B*, see also Fig. 1*C*) or even an absence of the static responses.

In the swimming lamprey, locomotor undulations of the body cause oscillations of the head with a frequency of 1–5 Hz, in the horizontal plane (Williams 1989), and in the roll plane (Deliagina, unpublished observation). We suggested that these oscillations might stimulate the vestibular organs and evoke responses in RS neurons, thus contributing to postural stabilization. To test this hypothesis, in four experiments on nonswimming lampreys, we manually applied periodical oscillations similar to those observed during swimming (3 Hz, 20° peak-to-peak, see METHODS) to the system that was otherwise unable to stabilize any postural orientation. With these oscillations added, the system became able to maintain the normal body orientation in all four experiments (Fig. 4*C*).

It is well known that periodical oscillations can arise in a closed-loop control system itself under certain conditions (see, e.g., Levine 1996). Usually the oscillations are considered undesirable, but in the system for postural stabilization in the lamprey they might play a positive role through additional stimulation of vestibular organs. To test this hypothesis, we used *circuit 2*, with in-built capacity for generating oscillations

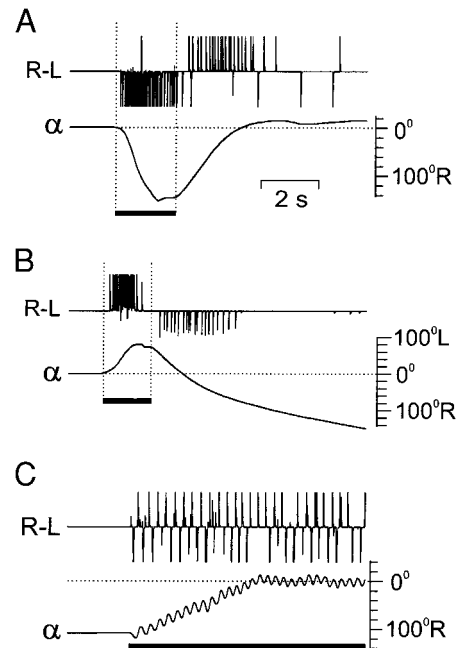


FIG. 4. Imposed oscillations promote stabilization of posture. Closed-loop conditions (*circuit 1*), nonswimming lamprey. *A*: recording was done in the experiment when the postural system was efficient, and compensated for the imposed deviation from the dorsal-side-up position (bar). *B* and *C*: a different experiment where the system was not efficient (*B*), but became efficient when periodical oscillations were imposed by the experimenter (*C*, bar).

(see METHODS and Fig. 2C), for processing the nervous signals. These experiments were carried out on nonswimming lampreys that were not capable of postural stabilization without imposed oscillations. In all tested animals ($n = 12$), the oscillating system was capable of stabilizing a certain orientation of the lamprey. If this orientation differed from the normal one (dorsal side up), we increased the amplification of the “weaker” signal to reach the normal orientation (Fig. 5A). In all experiments, we managed to precisely “tune” the system so that the mean value of the stabilized angle in different experiments was $0.5 \pm 1.4^\circ$ (mean \pm SD). With *circuit 2*, the system was always in motion (Figs. 5 and 6), and RS signals just changed the direction of rotation. The oscillations were caused by periodical excursions of the system between the angular zones of activation of the antagonistic groups of RS neurons. When the system entered a zone, a burst of activity of the corresponding RS neurons caused a reversal of the motor rotation.

Operation of the system was rather stable, and thus the relevance of system parameters on the operation could be examined. With a higher gain in the electronic circuit, a reversal of rotation could be caused by a lesser number of spikes, and even by a single (1st) spike generated by a neuron most sensitive to roll tilt (Fig. 5, B–D). Correspondingly, the frequency of oscillations tended to increase with a higher gain. The angular speed of rotation affected the frequency of oscillations. By varying the speed in the range of 10–100°/s, one could usually change the frequency of oscillations from ~ 0.5 to ~ 5 Hz. The value of the frequency was not critical for stabilization to occur, as illustrated in Fig. 5E, where postural orientation was maintained by the system oscillating at 1 Hz

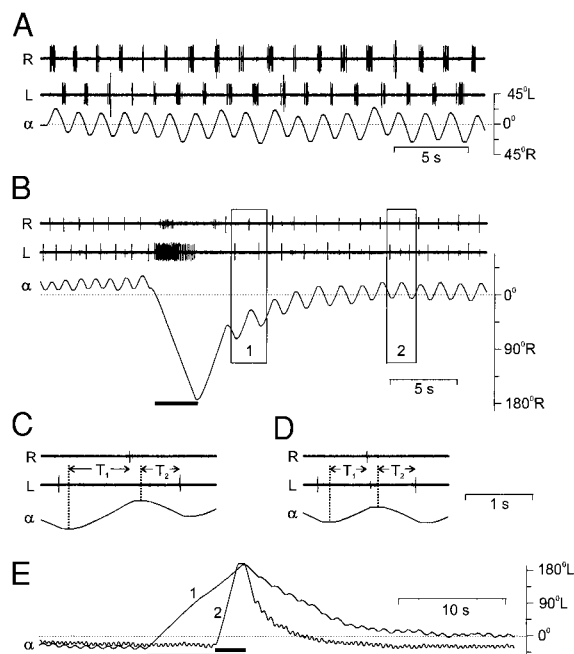


FIG. 5. Stabilization of postural orientation by the oscillating system (*circuit 2*). Activity of RS neurons was recorded from the right (R) and left (L) sides of the spinal cord. A: stabilization of the normal orientation, with low amplification in the electronic circuit. B: the same with high amplification in the circuit. Two parts of the recording in B (1 and 2) are shown in C and D, respectively, with a higher time resolution. E: the influence of the speed of rotation on the compensatory movement caused by a 180° imposed tilt; the speed was $20^\circ/\text{s}$ (curve 1) and $100^\circ/\text{s}$ (curve 2). Horizontal bars in B and E indicate imposed postural deviations (see text in RESULTS for further details).

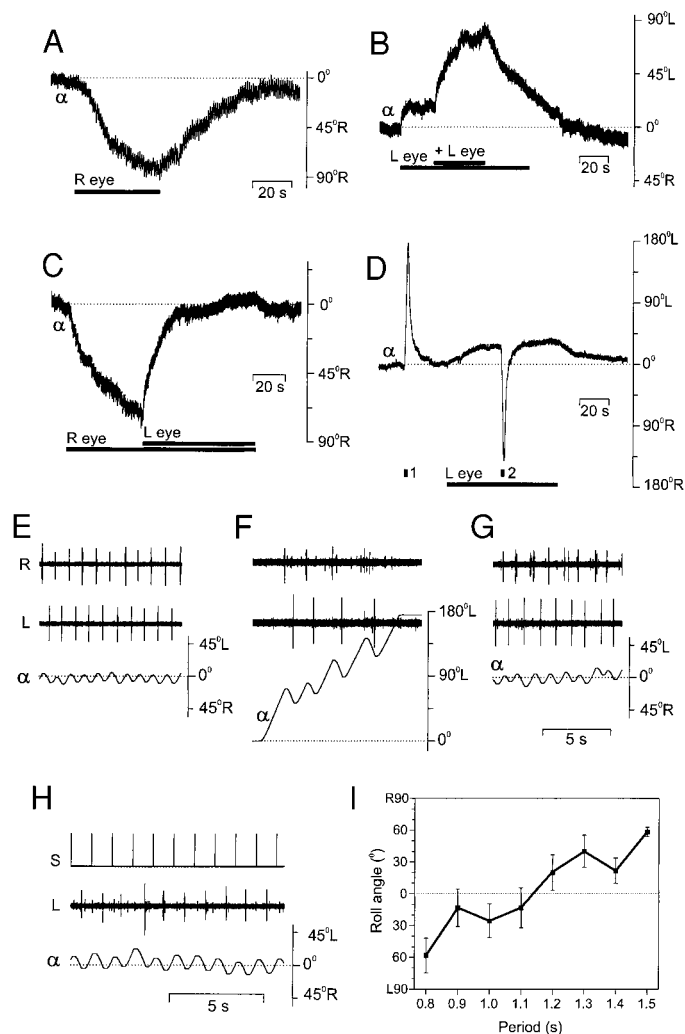


FIG. 6. Visuo-vestibular interactions in the postural network (nonswimming lamprey, *circuit 2*). A–D: simulation of the dorsal light response. A: response to illumination of the right eye. B: response to illumination of the left eye; a period of increased light intensity is indicated (+L eye). C: an initial response to the right eye illumination was compensated by the left eye illumination. D: postural corrections under 2 conditions, with no eye illumination and on the background of the dorsal light response caused by the left eye illumination. Bars 1 and 2 indicate imposed postural deviations, 180° left (1) and 180° right (2). E–G: loss of equilibrium after unilateral labyrinthectomy and its recovery caused by visual input. E: stabilization of the normal orientation before lesion. F and G: the same animal on the next day after removal of the left labyrinth exhibited a loss of equilibrium (F); the equilibrium could be restored by illuminating the right eye (G). H and I: simulation of the unilateral labyrinthectomy and compensation of the postural deficit. H: stabilization of the normal orientation in the experiment where one of the inputs to the electronic circuit was disconnected from the electrode, and instead it received pulses (with a period of 1.1 s) from the pulse generator (S). I: a stabilized orientation (mean roll angle \pm SD) as a function of the period of pulses delivered by the generator (30 tests in 1 animal).

(curve 1) and 2.5 Hz (curve 2). From Fig. 5E one can also see that the amplitude of oscillations was similar at both frequencies. In different experiments ($n = 12$) the amplitude of the oscillations was $9.5 \pm 5^\circ$ (mean \pm SD).

The oscillating system compensated for any disturbances of the postural orientation even in the absence of static vestibular reactions (Fig. 5, B and E). As shown in Fig. 5B, an imposed 180° tilt evoked activation of the contralateral RS neurons and was compensated for in a few seconds. The return to the

normal orientation was not smooth but oscillatory, however, due to the alternating dynamic vestibular responses to rotation in the left and right RS neurons, which resulted in a reversal of rotation. After a few oscillations, the system had approached the normal position. This striking result can be explained by the observation that the responses in RS neurons to leftward and rightward rotation occurred with different delay in relation to the point in time when a reversal of movement direction occurred, which is a reflection of asymmetry of the two dynamic reactions. As shown in Fig. 5C, the delay in activation of the left RS neuron (T_2), was shorter than for activation of the right RS neuron (T_1). Consequently, the leftward phase of oscillations was longer than the rightward phase, and the net movement of the system was in a leftward direction, i.e., toward the normal orientation. By contrast, during oscillations around 0° , the delays T_1 and T_2 were equal to each other (Fig. 5D) reflecting a symmetry of the two dynamic reactions. Postural stabilization is thus based on the dynamic vestibular reactions in RS neurons; the temporal characteristics of these reactions are position and velocity dependent.

Thus periodical oscillations of any origin (caused by locomotor undulations or arising in the control system itself) considerably improve postural stabilization due to additional activation of vestibular organs.

Visuo-vestibular interactions in the postural network

Visuo-vestibular interactions during postural stabilization were examined in nonswimming animals in which postural stabilization could be easily obtained by using the oscillatory circuit 2 (Fig. 2C), and visual stimulation could be easily combined with vestibular stimulation (Fig. 2A). In all tested animals ($n = 7$), under open-loop conditions, illumination of one eye elicited activation of ipsilateral RS neurons (not illustrated, see also Deliagina and Fagerstadt 2000). Under closed-loop conditions, the same stimulus evoked a roll tilt toward the illuminated eye (Fig. 6A), which is the reaction (dorsal light response) observed in freely behaving animals (Ullén et al. 1995b). As in the freely behaving animals, visually induced postural responses were relatively slow, with a rising phase of 5–25 s, and a decaying phase of 30–60 s in different experiments. The slowness of visual postural responses, as compared with vestibular ones, may explain the minor role of visual input for postural stabilization in the lamprey (Deliagina 1997a,b; Ullén et al. 1995b), in contrast to, e.g., the goldfish (Burt and Flohr 1991; Graf and Meyer 1983). The reaction to eye illumination was graded, as illustrated in Fig. 6B where an increase of light intensity caused an additional tilt. A reaction to illumination of one eye could be compensated for by illuminating the contralateral eye (Fig. 6C). The new position resulting from the eye illumination was actively stabilized by the vestibular-driven system, as was demonstrated by perturbing the postural equilibrium. As shown in Fig. 6D, an externally imposed left tilt (marked by *bar 1*) was rapidly compensated, and the system returned to the initial orientation (0°). A consistent roll tilt of 35° to the left was then evoked by illuminating the left eye. An externally imposed right tilt (*bar 2*) was rapidly compensated also in this situation; the system returned, however, not to 0° but to the currently stabilized orientation, that is a 35° tilt to the left.

The closed-loop oscillating system also allowed us to inves-

tigate visuo-vestibular interactions underlying compensation of a vestibular deficit. Removal of one vestibular organ in the lamprey results in a reduction of the resting activity and vestibular responses in RS neurons on the contralateral side (Deliagina et al. 1992b), and these animals roll continuously when they swim (Deliagina 1997a; Ullén et al. 1995a). The rolling can be terminated, however, by illuminating the eye on the intact side (Deliagina 1997b). We simulated this phenomenon in the present study. One of the experiments ($n = 3$) is illustrated in Fig. 6, E–G. With intact labyrinths, the dorsal-side-up orientation was stabilized (Fig. 6E). After removal of the left labyrinth, the system was not able to stabilize any particular orientation (Fig. 6F) because the reactions to roll tilt in the right RS neurons were weakened considerably, and the latency of their response to leftward roll was increased compared with the response in the left RS neurons to rightward roll. Illumination of the right eye resulted in a restoration of the tonic activity and vestibular responses in the right (deafferented) subgroup of RS neurons, and in a recovery of the postural control (Fig. 6G).

From these experiments it remained unclear, however, whether both components of activity in the deafferented RS neurons (tonic activity and roll-dependent activity) are necessary for the restoration of equilibrium. In a different set of experiments ($n = 2$), we simulated a loss of activity in one of the RS pathways (caused by a removal of the contralateral labyrinth) by disconnecting one of the inputs of the electronic circuit from the corresponding electrode. Driven by only one input, the system exhibited continuous rolling (not illustrated). Then we applied constant frequency pulses (delivered by an electronic pulse generator) to the free input of the circuit. Under these conditions, the system was again capable of postural stabilization (Fig. 6H). The stabilized angle depended on the pulse frequency, however (Fig. 6I). These results can be considered as a confirmation of the hypothesis that vestibular compensation (recovery after unilateral labyrinthectomy) can be partly based on the substitution of roll-dependent activity by tonic activity in the deafferented RS neurons (Deliagina 1997a). However, postural stabilization based on a unilateral roll-dependent command signal is far from perfection since it requires precise adjustments of the “compensatory” tonic signal to the command signal (Fig. 6J). Taken into account that the command signal depends not only on the tilt angle but also on the vigour of locomotion (Fig. 3, A and B), the problem of adjustments complicates dramatically. By contrast, the model based on the subtraction of symmetrical signals automatically compensates for any parallel changes of the two signals.

DISCUSSION

In the present study we used a novel technique for investigation of postural neural mechanisms. We substituted the output stage of the postural control system (the spinal network and the effector organs) with a simple electromechanical “robot” driven by biological signals, that is by the action potentials in RS axons. A transfer function of the robot could be set by the experimenter. With this method, we were able to answer a number of important questions regarding postural control that could be difficult to address with any traditional methods.

Decoding of supraspinal commands

Coding and decoding of space-related information in the sensory and motor centers of the CNS is one of the central problems in motor physiology (see, e.g., Georgopoulos 1995). We address some aspects of this problem by considering a relatively simple motor task: postural control in the lamprey, a lower vertebrate. In this animal, postural control mechanisms are driven mainly by vestibular input, and commands for postural corrections are transmitted from the brain stem to the spinal cord primarily by the RS pathways. Principles of coding of vestibular information in the commands transmitted by larger RS neurons were characterized in considerable detail in both *in vitro* experiments (Deliagina et al. 1992a) and *in vivo* experiments (Deliagina and Fagerstedt 2000; Deliagina et al. 2000b). Figure 1C shows how the body orientation and movement in a roll plane is reflected in the population activity of group 1 RS neurons in the intact lamprey (Deliagina and Fagerstedt 2000).

Much less is known, however, about the decoding of these commands in the spinal cord. A hypothesis was advanced that decoding is based on the subtraction of signals delivered by the left and right RS pathways, so that their difference determines the direction and value of corrective postural motor responses (Fig. 1B).

Investigation of the decoding of central commands by the spinal cord is not a trivial task, especially taking into account a complex dynamic nature of these commands (Fig. 1C), and the complexity of postural corrective responses (Ullén et al. 1995a). The present study is a first step toward solving this problem. In our neuro-mechanical model, the RS commands were natural, whereas a transfer function of the artificial output stage of the postural system was specified by the experimenter. The main result of the present study was that, when a difference between the left and right RS commands was used for the generation of postural corrective responses, the system was able to stabilize the normal body orientation (Fig. 3C). Moreover, a number of postural effects, characteristic for the lamprey, were reproduced using this system, including the dorsal light response (tilt toward the illuminated side, Fig. 6A), the effect of unilateral labyrinthectomy (continuous rolling, Fig. 6F), and compensation of this motor deficit by unilateral eye illumination (Fig. 6G).

Taken together, these results provide a strong support to the initial idea (see Deliagina 1997a; Deliagina et al. 1993) (and see Fig. 1B) that postural stabilization in the lamprey is based on the two antagonistic vestibulo-reticulospinal reflexes, and that interaction of the two descending commands (their subtraction) occurs in the output stage of the system. One of the possible sites for this interaction is the segmental network with its system of reciprocal inhibition between the two hemisegments (Cohen and Harris-Warrick 1984; Grillner and Wallén 1980; Wallén et al. 1993). Our recent experiments have demonstrated a high efficacy of this system in subtracting the left and right reticulospinal commands (Fagerstedt et al. 2000). A different site is the effector organs (left and right myotomes) opposing each other. Since the left and right myotomes are not usually coactivated during locomotion (see, however, Deliagina et al. 1995), the former hypothesis seems more likely. Further studies of the spinal neuronal network responsible for transformation of descending commands into postural correc-

tions are needed, however, before we can say how these effects are produced. Presently we are investigating the effects of individual RS neurons on the segmental motor output.

In the neuro-mechanical system used in the present study, the RS signals were able to stabilize postural orientation with very different designs and characteristics of the output stage of the system, e.g., 1) when the speed of rotation depended on the value of command signals (*circuit 1*, Fig. 2B), or when it did not (*circuit 2*, Fig. 2C), and 2) when the long burst is integrated to generate the command signal (Fig. 5A) or only the first spike is used (Fig. 5B). These results strongly suggest that our conclusions regarding decoding of the RS commands for postural corrections are not linked to any specific dynamic characteristics of the output stage.

Postural control systems are often considered as systems operating on the basis of signals that monitor deviation of the regulated variable (body axis, position of the center of mass, etc.) from its optimal value (the "central concept" of postural control) (Massion 1994). Such signals have not been found in the present study, neither in the study on the mollusk *Clione* (Deliagina et al. 1998). These studies have rather shown that postural control in "simpler" animals is based on interaction between two opposing reflexes, and monitoring the regulated variable is not necessary. This result supports the "reflex concept" of postural control (Magnus 1924), and well fits to the general idea of Gelfand and Zetlin (1971), who proposed the "nonindividualized" ("nonaddressed") mode of control in complex systems, where only the highest levels of the system have the full notion about the final task while the main "effectors" act on the basis of very limited information and are solving their "particular" problems.

Experiments with eye illumination (Fig. 6, A–D) have clearly demonstrated that the postural control system in the lamprey can effectively operate in a wide range of roll angles, and that a transition from one stabilized orientation to the other is caused by a shift of the equilibrium point in the vestibular-driven postural network. This principle substantially differs from that revealed in the postural system of the mollusk *Clione*. This system is also driven by gravitational input, but modifications in the postural orientation are based on a reconfiguration of the postural network (Deliagina et al. 1998, 2000a).

Role of dynamic component in command signals

The dynamic component of vestibular response in RS neurons (activity during movement) is much stronger than the static one (activity in a sustained new position); both components are position dependent and directionally sensitive (Fig. 1C). It is evident that the system with such command signals will better compensate for rapid deviations from the stabilized orientation (since they evoke stronger dynamic responses) than for slow ones. As shown in the present study, the system without static reactions can even stick in some positions, or produce continuous slow rolling (Fig. 4B). We have suggested that small but rapid oscillations, superimposed on the postural orientation, will improve operation of the postural system due to additional activation of vestibular organs. This hypothesis was directly confirmed when oscillations that mimicked locomotor undulations were applied to the system (Fig. 4C). Similarly, the oscillations generated by the control system itself

considerably improved postural performance (Fig. 5). A possible mechanism for generating periodical oscillations in the postural network is the internal feedback based on "efference copy" signals coming to the brain stem from the spinal locomotor network (Kasicki et al. 1989; Vinay and Grillner 1992). These signals produce rhythmical modulation of RS activity (Fig. 3B) and may thus rhythmically affect the postural orientation. One can suggest a similar functional role of the rhythmical modulation of RS activity revealed in other species (Drew et al. 1986; Orlovsky 1970).

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