Organization of Recurrent Inhibition and Facilitation in Motor Nuclei Innervating Ankle Muscles of the Cat

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Turkin, Vladimir V., Katrina S. Monroe, and Thomas M. Hamm. Organization of recurrent inhibition and facilitation in motor nuclei innervating ankle muscles of the cat. J. Neurophysiol. 79: 778–790, 1998. The distribution of recurrent inhibition and facilitation to motor nuclei of muscles that act at the cat ankle joint was compared with the locomotor activity and mechanical action of those muscles described in published studies. Emphasis was placed on motor nuclei whose muscles have a principal action about the abduction—adduction axis and the pretilial flexors: tibialis posterior (TP), peroneus longus (PerL), peroneus brevis (PerB), the anterior part of tibialis anterior (TA) and extensor digitorum longus (EDL). Most intracellular recordings in spinalized, unanesthetized decerebrate cats showed only inhibitory or excitatory responses to antidromic stimulation of peripheral nerves, but mixed effects were also seen. Recurrent effects among motor nuclei of ankle abductors and adductors were not distributed uniformly. TP motoneurons received recurrent inhibition from most other nuclei active in stance and stimulation of the TP nerve inhibited these motor nuclei. Although PerB motoneurons are also active during stance, they received primarily facilitation from most motor nuclei. PerL received mixtures of inhibition and facilitation from all sources. Stimulation of the nerves to PerL, PerB, and peroneus tertius (PerT) produced weak recurrent inhibition and facilitation, even in homonymous motoneurons and motoneurons of Ia synergists. The ankle flexors TA and EDL displayed different patterns of recurrent inhibition and facilitation. TA motoneurons received prominent homonymous inhibition and inhibition from semitendinosus (St). EDL, whose activity profile differs from TA and which also acts at the digits, did not receive strong recurrent inhibition from either TA or St, nor did stimulation of the EDL nerve produce much inhibition. The distribution of recurrent inhibition and facilitation is correlated with the pattern of locomotor activity, but with exceptions that suggest an influence of mechanical action, particularly in the antagonistic interactions between TP and PerB. The extended pattern of recurrent inhibition, the reduction or absence of inhibition produced by motor nuclei with individualized functions or digit function and the prevalence of facilitation suggest that the recurrent Renshaw system is organized into inhibitory and disinhibitory projections that participate in the control of sets of motor nuclei engaged in rhythmic and stereotyped movements.

INTRODUCTION

Recent investigations of Renshaw recurrent inhibition have provided comparative data on its distribution to motor nuclei that innervate muscles of the upper and lower limbs in human subjects and muscles of the fore- and hindlimbs in cats. Although prominent in motor nuclei that innervate the proximal muscles of a limb, recurrent inhibition is often absent or reduced in motor nuclei that innervate distal musculature, particularly those acting at the digits, in both the cat (Hahne et al. 1988; Hamm 1990; Horner et al. 1991; McCurdy and Hamm 1992) and human (Katz et al. 1993; Rossi and Mazzucchelli 1991). The patterns of recurrent inhibition differ between these limb systems, particularly those involving motor nuclei that innervate muscles acting at different joints (Katz et al. 1993; Meunier et al. 1990, 1994). These variations in the distribution of recurrent inhibition suggest that its organization has been adapted to meet different requirements for the control of these various limb systems and the proximal and distal musculature of each limb.

Some investigators have noted that differences in the patterns of recurrent inhibition between the motor nuclei of human (Katz et al. 1993; Meunier et al. 1990, 1994) and cat (Baldiserra et al. 1981) limb systems correspond to differences in the pattern of Ia facilitation and have suggested that recurrent inhibition limits the extent of Ia excitation and Ia reciprocal inhibition and increases the contrast between motor patterns in proximal motor nuclei, as postulated in earlier investigations (Brooks and Wilson 1959; Hultborn et al. 1971a; see also Hultborn et al. 1979). Also, Windhorst (1996) has proposed that recurrent inhibitory and Ia projections form an integrated system for parameter adjustment of spinal networks employed in stabilizing posture and movement.

Despite the similarities between the patterns of recurrent inhibition and Ia facilitation, there are also mismatches in each limb system, such that heteronymous Ia facilitation occurs without the corresponding recurrent inhibition, or heteronymous recurrent inhibition occurs without corresponding Ia projections, as shown both in human (Creange et al. 1992; Katz et al. 1993; Meunier et al. 1994) and cat studies (Baldiserra et al. 1981; Fritz et al. 1989; Hahne et al. 1988; Hamm 1990; Horner et al. 1991; Illert and Wietelmann 1989). For example, the cat flexor hallucis longus and flexor digitorum longus exchange strong Ia monosynaptic excitation (Dum et al. 1982), but display very different patterns of activity during normal and fictive locomotion (O’Donovan et al. 1982; Fleshman et al. 1984; Trank et al. 1996). The patterns of recurrent inhibition and facilitation received by the motor nuclei of these muscles reflect the differences in activity during locomotion, rather than their Ia synergism (Hamm 1990), suggesting that patterns of recurrent inhibition reflect the organization of locomotor activity rather than patterns of Ia projections. Alternatively, the patterns of recurrent inhibition could reflect the mechanical requirements for the control of each limb, which would find their counterparts.
in the organization of other spinal circuits, like Ia facilitation and reciprocal inhibition, and in the organization of locomotor commands.

The goal of the investigation reported here was to determine the distribution of recurrent inhibition and facilitation to motor nuclei that act at the ankle in the cat, for comparison to the mechanical actions and patterns of activity in these muscles and their motor nuclei. Previous studies of recurrent inhibition in motor nuclei of ankle muscles principally have been concerned with its distribution between ankle extensors and between the ankle extensors and the pretibial flexors as a group (Eccles et al. 1961a; Hultborn et al. 1971a; Hamm 1990), but little information is available on the distribution of recurrent inhibition and facilitation within the pretibial flexors or between adductors and abductors of the ankle. Our studies show that recurrent inhibition and facilitation are not uniformly or symmetrically distributed between these motor nuclei and that the patterns of recurrent inhibition and facilitation are correlated with patterns of locomotor activity and mechanical action.

METHODS

The data reported in this study were obtained from 10 adult cats (3–4.5 kg). For initial surgical procedures, each cat was anesthetized with a mixture of isoflurane, nitrous oxide, and oxygen. Anesthesia was induced in a plexiglass chamber. After induction, anesthetic was delivered via a mask until a tracheal cannula was inserted for continued administration of anesthetic and ventilation. Isoflurane concentration was adjusted over a range of 1.7 to 2.1% to maintain a surgical level of anesthesia. Catheters were placed in one common carotid artery and external jugular vein for measurement of arterial blood pressure and administration of fluids and drugs, respectively. In addition, a catheter was placed in the urethra.

A lumbosacral laminectomy was performed to expose segments L4-S1 and a hindlimb dissection was performed to expose several muscle nerves for stimulation. The following muscle nerves were carefully dissected free from surrounding tissue, sectioned and placed on bipolar electrodes: the nerves to anterior biceps femoris (ABF), semitendinosus (St), lateral gastrocnemius and soleus (LGS), plantaris (Pla), flexor hallucis longus (FHL), tibialis posterior (TP), peroneus longus (PerL), peroneus brevis (PerB), peroneus tertius (PerT), the anterior part of tibialis anterior (TA), and extensor digitorum longus (EDL). The nerve branch to the posterior part of tibialis anterior was also dissected free and mounted for stimulation. However, we subsequently discarded postsynaptic potentials (PSPs) produced by stimulation of this nerve branch and motoneurons identified as innervating this branch because of concern about possible inadvertent activation of the nerve to extensor digitorum brevis. The spinal cord was transected at segment T13-L1 after injection of 5 mg of lidocaine hydrochloride into the dorsal columns and lateral funiculi.

After surgical procedures, the cat was mounted on a steel recording table by the use of vertebral clamps at T3, L3, and the sacrum. Each cat was decerebrated at the midcollicular, postmammillary level. The cerebral hemispheres were removed and the dura was opened and dorsal roots from L5 to S2 were sectioned. Ventral roots L7 and S1 were placed intact on monopolar hook electrodes made of stainless steel to monitor antidromic volleys. The sectioned muscle nerves were placed on bipolar electrodes for stimulation. The exposed spinal cord and all nerves were covered with warm paraffin oil. The temperature of the oil bath was monitored and regulated at 37°C with a servo-controlled heating mat and radiant heat.

Intracellular recordings from motoneurons were made with the use of glass microelectrodes, filled with 2 M K + citrate. Averages of recurrent responses produced by stimulation of muscle nerves at three times motor threshold were collected with the use of an oscilloscope with an averaging function and a CED interface controlled by a personal computer. Each average consisted of 32 samples. Sometimes two or three sets of 32 samples of the responses from a muscle nerve were recorded, particularly for small responses. Determinations were made of conduction velocity and, if recording conditions remained stable, of input resistance and rheobase. Input resistance was determined from injection of several current pulses of 50 ms duration and amplitudes of ±2 nA or less. The amplitude of a 50 ms current pulse required to evoke discharge in approximately one-half the trials was accepted as rheobase.

The measurements of resting potential and action potential amplitude were made just after impalement and just before the electrode was withdrawn from the cell. Only motoneurons with action potentials of at least 60 mV or resting potentials of at least 50 mV were accepted for study. In some cases, especially for small responses, extracellular controls for the recurrent responses were also recorded and subtracted from the corresponding intracellular average to remove the effects of any field potentials. We did not find that field potentials introduced significant distortions of the intracellular potentials in these preparations. Averages were accepted as recurrent IPSPs (RIPSPs) or recurrent facilitatory potentials (RFPs) if the amplitude was large enough (typically 0.1 mV) for the potential to be distinguished from background noise and the waveforms had a typical latency and profile for these potentials.

Two or three averages were collected, the response was only accepted if it was consistent in the different averages.

RESULTS

Characteristics of motor nuclei and muscles investigated

We determined patterns of recurrent inhibition and facilitation between motor nuclei of nine ankle muscles and two proximal muscles that exert various mechanical actions and display a range of locomotor activities. The focus of the current study concerns the projections to and from motor nuclei that have received less attention in previous studies of recurrent inhibition - TP, PerL, PerB, PerT, TA and EDL. Projections involving other motor nuclei are discussed when our results differ from or expand on previous results. The mechanical action and pattern of locomotor activity of the muscles innervated by these motor nuclei are summarized in Table 1.

The distribution of recurrent inhibition was compared with locomotor activity and mechanical actions to answer several questions. 1) Are the motor nuclei whose activation produces recurrent inhibition in a motor nucleus the same as those that produce similar patterns of locomotor activity? 2) Does the amount of recurrent inhibition received by a motor nucleus and produced by its activation depend on its expression of stereotyped patterns of locomotor activity (cf. the rheobase. Input resistance was determined from injection of several current pulses of 50 ms duration and amplitudes of ±2 nA or less. The amplitude of a 50 ms current pulse required to evoke discharge in approximately one-half the trials was accepted as rheobase.

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Activity in locomotion indicates phase of step cycle in which each muscle is active; the classification for St indicates 2 bursts per step cycle, starting just before the start of paw lift, and before that start of paw placement. Description of locomotor patterns is based on Abraham and Loeb (1985); Engberg and Lundberg (1969); Loeb (1993); O’Donovan et al. (1982); and Trank et al. (1996). Mechanical actions at the ankle are given according to the results of Lawrence et al. (1993) and Young et al. (1993) and actions at other joints have been inferred from the origin and insertion of each muscle. Secondary (or weak, for PerT) actions are given for the ankle in lower case, except for Pla, which has little action outside the sagittal plane at neutral joint positions (T. R. Nichols, personal communication). The data of Young et al. (1993) express the mean moment arm of each muscle as a function of joint angle, whereas, Lawrence et al. (1993) gives a single torque value at a neutral joint position. For muscles in which the moment arm changes sign with joint angle, the action listed refers to a joint position in which the data of Lawrence et al. (1993) and Young et al. (1993) are in agreement, or of the predominant action. Dorsiflexion and plantarflexion of the ankle are referred to as flexion and extension, respectively, a convention followed throughout the paper. ABF, anterior biceps femoris; LGS, lateral gastrocnemius; Pla, plantaris; FHL, flexor hallucis longus; TP, tibialis posterior; PerB, peroneus brevis; St, semitendinosus; TA, tibialis anterior; EDL, extensor digitorum longus; PerL, peroneus longus; PerT, peroneus tertius. * Activities marked with asterisks indicate those which are variable in different animals (PerL, PerT) or mutable with different speeds or forms of locomotion, as discussed in the text. ** The plantarflexion action at the toes of Pla is indirect, acting through an in-series arrangement with flexor digitorum brevis (Brooks et al. 1992; Goslow et al. 1972).

McCurdy and Hamm (1992)? 3) Do motor nuclei whose muscles act as agonists (or antagonists) at the ankle produce recurrent inhibition (or facilitation) in one another when activated? 4) Do motor nuclei whose muscles act at the digits produce and receive less recurrent inhibition?

These comparisons were made on the basis of data from 127 intracellularly recorded motoneurons of the 11 motor nuclei. Table 2 presents the characteristics of the cells that were investigated. There were no prominent differences in spike amplitude, rheobase, or input resistance between species of motoneurons. The samples from these motoneuron pools did differ in conduction velocity, as indicated by an analysis of variance (ANOVA; $F = 2.62; P = 0.007$). A posthoc test (Duncan critical range test) demonstrated that the mean conduction velocities of the PerB, PerT, and EDL samples were less than those of the ABF, Pla and TP samples.

### Table 1. Pattern of locomotion and mechanical action of investigated muscles

<table>
<thead>
<tr>
<th>Muscle</th>
<th>Activity in Locomotion</th>
<th>Mechanical Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABF</td>
<td>Stance</td>
<td>Hip/Knee</td>
</tr>
<tr>
<td>LGS</td>
<td>Stance</td>
<td>Ankle</td>
</tr>
<tr>
<td>Pla</td>
<td>Stance</td>
<td>Toes</td>
</tr>
<tr>
<td>FHL</td>
<td>Stance</td>
<td>Flexion-plantarflexion**</td>
</tr>
<tr>
<td>TP</td>
<td>Stance</td>
<td></td>
</tr>
<tr>
<td>PerB</td>
<td>Stance/Swing*</td>
<td></td>
</tr>
<tr>
<td>TA</td>
<td>Swing</td>
<td></td>
</tr>
<tr>
<td>EDL</td>
<td>Swing*</td>
<td></td>
</tr>
<tr>
<td>PerL</td>
<td>Variable*</td>
<td></td>
</tr>
<tr>
<td>PerT</td>
<td>Variable*</td>
<td></td>
</tr>
</tbody>
</table>

### Table 2. Characteristics of motoneurons sampled from the investigated motor nuclei

<table>
<thead>
<tr>
<th>Muscle</th>
<th>ABF</th>
<th>St</th>
<th>LGS</th>
<th>Pla</th>
<th>FHL</th>
<th>TP</th>
</tr>
</thead>
<tbody>
<tr>
<td>CV</td>
<td>97.8 ± 17.7</td>
<td>86.7 ± 8.2</td>
<td>91.5 ± 14.</td>
<td>97.5 ± 13.1</td>
<td>90.5 ± 11.1</td>
<td>97.3 ± 14.2</td>
</tr>
<tr>
<td>65–121 (12)</td>
<td>79–104 (10)</td>
<td>74–113 (10)</td>
<td>77–122 (13)</td>
<td>68–104 (12)</td>
<td>82–120 (6)</td>
<td></td>
</tr>
<tr>
<td>$R_s$</td>
<td>1.35 ± 0.79</td>
<td>1.59 ± 0.84</td>
<td>1.03 ± 0.47</td>
<td>1.66 ± 0.86</td>
<td>1.79 ± 0.78</td>
<td>1.72 ± 1.0</td>
</tr>
<tr>
<td>0.6–2.9 (9)</td>
<td>0.5–3.2 (11)</td>
<td>0.4–1.8 (7)</td>
<td>0.4–3.3 (9)</td>
<td>1.0–3.3 (10)</td>
<td>0.7–3.4 (5)</td>
<td></td>
</tr>
<tr>
<td>$I_R$</td>
<td>11.4 ± 4.8</td>
<td>11.9 ± 7.0</td>
<td>11.6 ± 4.9</td>
<td>11.6 ± 6.0</td>
<td>10.7 ± 4.4</td>
<td>18.2 ± 15.5</td>
</tr>
<tr>
<td>$S_A$</td>
<td>67.8 ± 7.1</td>
<td>73.0 ± 10.1</td>
<td>73.0 ± 7.5</td>
<td>70.2 ± 6.4</td>
<td>76.3 ± 9.7</td>
<td>5.7 ± 9.8</td>
</tr>
<tr>
<td>57–80 (10)</td>
<td>60–90 (11)</td>
<td>60–80 (9)</td>
<td>60–80 (13)</td>
<td>60–90 (12)</td>
<td>65–90 (6)</td>
<td></td>
</tr>
</tbody>
</table>

The mean, standard deviation, and range of values of conduction velocity (CV in m/s), input resistance ($R_s$ in $\Omega$), rheobase ($I_R$ in nA), and spike amplitude ($S_A$ in mV) are given for each motor nucleus. The number of cells on which each measurement was made is given in parentheses. Measurements of all variables were not made in all motoneurons. Input resistance and rheobase were not determined if the condition of the cell deteriorated. Values for spike amplitude do not include spikes in which the SD component was blocked. In three cases CV was not determined because of an inadvertent failure to place the recordings on tape for subsequent analysis. For abbreviations, see Table 1.
FIG. 1. This figure gives examples of averaged recurrent postsynaptic potentials, showing different combinations of recurrent inhibition and facilitation recorded in motoneurons innervating ankle muscles. A: recurrent inhibitory postsynaptic potentials (RIPSPs) in a motoneuron innervating lateral gastrocnemius-soleus (LGS) muscle in response to stimulation of tibialis posterior (TP) nerve. B: recurrent facilitatory potentials (RFPs) in a tibialis anterior (TA) motoneuron in response to LGS nerve stimulation. C–E: responses with different mixtures of facilitation and inhibition. Response recorded in a TP motoneuron to stimulation of anterior biceps femoris (ABF) nerve is shown in C; inhibition and facilitation recorded in a flexor hallucis longus (FHL) motoneuron in response to stimulation of ABF nerve is shown in D; and E shows brief inhibition followed by facilitation in an extensor digitorum longus (EDL) motoneuron after stimulation of semitendinosus (St) nerve. Zero on time axis indicates arrival of motor volley in ventral roots. Each average consisted of 32 samples. Strength of stimulation of muscle nerves was 3 times motor threshold.

Characteristics of the recorded responses

Both inhibition and facilitation were recorded in our sample of motoneurons. Most responses were either inhibitory (317 responses; 38%) or facilitatory (311 responses; 38%), but responses in which inhibition was followed by facilitation were often observed (199 responses; 24%). Thus facilitation contributed to over half the responses. Examples of each of these forms of responses are shown in Fig. 1. Mixed responses in which facilitation followed inhibition displayed several forms. They sometimes consisted of a brief hyperpolarization followed by facilitation (Fig. 1E), as noted previously for antagonists (Renshaw 1941; Wilson et al. 1960). The initial IPSP in such responses could be as brief as 5 ms in some cases. The possibility that these IPSPs were actually extracellular fields was excluded by direct comparison to extracellular fields of motoneurones produced by antidromic invasions were invariably shorter. In homonymous connections or in projections to synergists, longer lasting inhibition (25–55 ms) was often followed by facilitation (Fig. 1D). In addition, mixed responses were also observed in which the inhibition was of intermediate duration (Fig. 1C).

Several lines of evidence indicate the RFPs were not reversed IPSPs. The range of resting potentials in most cells was 55–65 mV, potentials at which IPSPs should not be reversed. Secondly, many cells produced a mixture of IPSP and RFPs in response to stimulation of different nerves. Although some species showed mainly RFPs, resting potentials in these cells were similar to those of other species. In 13 cases depolarizing current (10–15 nA) was injected to determine if the facilitation was actually a reversed IPSP. This sample included nine PerB motoneurons, and one each from PerT, PerL, EDL, and LGS. Injection of depolarizing current never reversed or reduced the magnitude of the facilitatory responses.

Responses with facilitation, either with or without inhibition, were found in most projections between motor nuclei, including homonymous projections, projections between synergists, and projections between antagonists. In fact few projections between motor nuclei failed to provide one or
more examples of some form of facilitatory response. We also observed that some motoneurons in a pool received inhibition, although others received facilitation from the same source. A notable example of this mixture of inhibition and facilitation was found in PerL motoneurons (Figs. 2 and 3), but mixtures to lesser extents were found in other motoneuron pools as well.

Patterns of inhibition and facilitation for TP motoneurons

Figure 2 shows examples of RIPSPs and RFPs recorded in TP motoneurons. As shown in this figure, stimulation of LGS and Pla produced inhibition in TP motoneurons. The inputs from all motor nuclei are summarized in Fig. 3, showing that inhibition of TP motoneurons was mainly produced by stimulating nerves of ankle muscles active in stance, LGS, Pla, and FHL, regardless of their action in the adduction-abduction plane. Stimulation of the ABF muscle nerve produced inhibition in only two of the six motoneurons, although the amplitude of this inhibition was relatively large. Three of the other TP motoneurons received monophasic RFPs from ABF. Weak inhibition was received from PerL by most TP cells and four of six received inhibition from either EDL or TA. The inhibition from most of these sources was frequently mixed with facilitation.

Prominent homonymous inhibition was seen in TP motoneurons (Fig. 2), despite the small size of this nucleus (60 alpha motoneurons; Boyd and Davey 1968). Stimulation the TP nerve inhibited most FHL motoneurons and produced inhibition in LGS motoneurons comparable in amplitude to the homonymous inhibition. Weak inhibition was also produced in the majority of ABF and TA motoneurons, while in EDL cells input from TP was evenly mixed between inhibition and facilitation. Most PerL and PerB motoneurons received facilitation in response to TP stimulation.

In general, stimulation of the TP nerve inhibits motor nuclei that also express stance-phase locomotor activity and TP motoneurons receive recurrent inhibition from these same motor nuclei. Two exceptions to this finding occur in cases in which the muscle of a motor nucleus opposes the action of TP or shares its mechanical action. PerB is the antagonist of TP in adduction-abduction, and its motor nucleus is facilitated by TP activation, despite similar activity during stance. On the other hand, activation of TA or TP produces inhibition in some motoneurons of the other motor nucleus, even though these motor nuclei are active in different phases of the step cycle. In this case, TA shares TP’s adductor action when the ankle is abducted.

Patterns of inhibition and facilitation for Perl, Perb, and Pert motoneurons

The PerL and PerB muscles, like TP, have substantial moment arms about the adduction-abduction axis of movement. Like TP, activation of these motor pools produces recurrent effects, consistent with a previous report that these
motoneurons possess recurrent collaterals (Horcholle-Bossavit et al. 1988). However, recurrent effects from these motor nuclei are weak and recurrent effects received by these motor pools are dominated by recurrent facilitation.

PerB motoneurons received RFPs in response to stimulation of the ABF, St, LGS, Pla, and FHL nerves, in addition to TP (Figs. 2, 3). Thus PerB motoneurons did not receive inhibition from other motoneuron pools that are also active during stance (ABF, LGS, Pla, TP, and FHL), as TP does, nor from a motor nucleus whose innervated muscle produces ankle abduction (LGS). Stimulation of the PerB, PerL, or PerT nerve only occasionally produced RIPSPs in PerB motoneurons and these were small (Fig. 3).

Stimulation of the PerB nerve produced only small recurrent effects and in a minority of motoneurons. Small RIPSPs were seen most often in LGS, St, and FHL, although RFPs were produced in these same pools. In fact, the motoneurons of most motor pools could receive either small RIPSPs or small RFPs in response to stimulation of the PerB nerve (Fig. 3).

PerL motoneurons received very mixed effects from most motor nuclei. Individual PerL motoneurons could receive RIPSPs, RFPs or mixed responses (Figs. 2, 3). Facilitation was largest and found most frequently from motor nuclei active during the stance phase of locomotion, although some facilitation was received from all sources. The Ia synergists PerB and PerT (Eccles et al. 1962) were sources of facilitation, in addition to the PerL pool itself. Inhibition was found from each of the peroneal motor nuclei, but its magnitude and prevalence were no greater than from the other motor nuclei we examined.

Locomotor activity in PerL has been reported to vary between cats (Loeb 1993) and the secondary moment arm can vary between flexion and eversion in different animals (Young et al. 1993). Kernell and his colleagues have also reported that different portions of the PerL muscle may be differentially active during some forms of motor behavior and are differentially activated by segmental and descending inputs (Hensbergen and Kernell 1992; Kandou and Kernell 1989). We reviewed the responses in each PerL cell to determine if the mixture of inhibition and facilitation resulted from differences in input to PerL motoneurons in distinct populations of PerL motoneurons or in different animals. We found that all but two PerL cells received mixtures of inhibition and facilitation and that the pattern of inhibition and facilitation varied from cell to cell. There did not appear to be distinct patterns in two groups of cells that accounted for the mixture. Nor did we find a particular pattern associated with each cat. Inhibition and facilitation from each nerve were found in nearly every experiment, except for RIPSPs from ABF and PerB and RFPs from PerT, each of which only occurred in two of the six cats in which we recorded PerL motoneurons.

As in the case of PerB, stimulation of PerL produced only
small effects and only in a minority of motoneurons. PerL produced RFPs in St and LGS. Inhibition was produced most frequently in TA and TP motoneurons, although this inhibition was small.

PerT consists of just 34 alpha motoneurons (Hor cholle-Bossavit et al. 1988). We recorded a complete set of responses in two PerT motoneurons and a partial set in a third. These PerT motoneurons received facilitation from most nerves (e.g., Fig. 2). No inhibition was observed in three cells from PerL, or in one cell each tested for input from PerB or PerT. Stimulation of PerT produced small recurrent effects in some motoneurons, including slight facilitation in ABF and St, and slight mixed effects in FHL and EDL (data not shown). Although RIPSPs were seen in some PerL and PerB motoneurons, facilitation was recorded as often in PerL motoneurons (4 of 17 cells) and more often in PerB motoneurons (3 of 7 versus 1 of 7 cells).

In summary, PerB produces consistent stance phase activity in locomotion, but activation of this motor nucleus does not produce inhibition in other motor nuclei active in stance, nor is PerB inhibited by activation of these motor nuclei. Rather, PerB is facilitated by activation of its stance phase synergists. Considering its mechanical action, PerB is facilitated by activation of its primary adductor antagonist, TP, as well as by FHL, but facilitation is also provided by motor nuclei whose muscles act at other joints (ABF, St) or have a secondary action as ankle abductors (LGS). Both PerL and PerT express variable patterns of locomotion and these motor nuclei receive either variable mixtures of facilitation and inhibition (PerL) or facilitation (PerT) from nearly all motor nuclei that were tested. They produce little recurrent inhibition or facilitation. PerT’s primary mechanical action is to abduct the fifth digit. There was not an obvious correlation in the pattern of inhibition and facilitation to PerL’s primary mechanical action as abductor, but this comparison is complicated by the variability of its secondary mechanical action (Table 1).

Patterns of inhibition and facilitation for TA and EDL motoneurons

A previous study from this laboratory (Hamm 1990) reported that EDL motoneurons received some recurrent inhibition from extensor motor nuclei. Unlike TA, the locomotor activity of EDL remains strong during the latter part of the swing phase and overlaps the initial extensor burst at the start of stance when the extensor motor pools are active (Abraham and Loeb 1985; Engberg 1964; Goslow et al. 1977; Trank et al. 1996). The data from the present study provide only partial confirmation of previous results; inhibition from Pla and FHL was weaker than found by Hamm (1990). The present result do show differences in the participation of TA and EDL in recurrent circuits. TA motoneurons received prominent inhibition from stimulation of nerves innervating both proximal and distal muscles (Figs. 4 and 5). The largest RIPSPs recorded in TA motoneurons were evoked by stimulation of the homonymous and St nerves. Stimulation of the nerve supplying EDL produced only small IPSPs and in only half of the TA motoneurons. In a previous study (unreported data from Hamm 1990) stimulation of the EDL nerve failed to evoke recurrent IPSPs in six TA motoneurons. TP and PerL nerve stimulation also evoked small RIPSPs in some TA motoneurons. Large RFPs were evoked in TA motoneurons on stimulation of the ABF, LGS and, less frequently, Pla nerves. (cf. Wilson et al. 1960).

Stimulation of TA produced strong inhibition in most St motoneurons and inhibition in half the TP cells (with one case of facilitation). Inhibition was also found in 14 of 22 EDL motoneurons, although this inhibition was considerably weaker than that evoked in St motoneurons and similar to that received by TP motoneurons. Recurrent facilitation was found most frequently in the PerL and PerB motoneuron pools. In a few instances small RIPSPs were found in LGS motoneurons.

In contrast to TA cells, EDL motoneurons received only slight inhibition from TA and St (Fig. 4). There was little homonymous inhibition. Facilitation was seen after stimulation of the ABF, LGS, and Pla nerves, although the amplitude of this facilitation was smaller than observed in TA motoneurons. Stimulation of the LGS and Pla nerve evoked inhibition in some EDL motoneurons.

As noted above, RIPSPs from EDL in TA and EDL motoneurons were small and were observed in approximately half of these neurons. In contrast to the effect of stimulating TA, activation of EDL produced inhibition in a minority of St cells. EDL produced small amounts of inhibition in some LGS motoneurons (e.g., Fig. 4), with facilitation following inhibition in only one of these cells.

St, TA, and EDL are active in the swing phase of locomotion, although the phasing of their activities differs. The recurrent inhibition between EDL and TA is weak, in contrast to the inhibition between TA and St. The locomotor activity produced by both St and EDL is variable, but the central mechanisms underlying this variability may differ (see DISCUSSION). The differences between TA and EDL occur despite their primary action in dorsiflexion, but EDL is also a prominent toe dorsiflexor.

Patterns of inhibition and facilitation for proximal group of motoneurons

Our data concerning inhibition between the motor nuclei innervating ABF, St, LGS, Pla, and FHL are in general agreement with previous observations (Eccles et al. 1961a; Hultborn et al. 1971a). Consistent with the results of Hultborn et al. (1971a), we found small amounts of recurrent inhibition from LGS to St (mean amplitude: 0.22 mV), but found recurrent facilitation more often than in that previous study. Weak facilitation was observed in St, LGS, and Pla motoneurons; the strongest projection was from ABF to St (mean of 0.22 mV). In turn, facilitation was found from St to ABF, as well as to LGS and Pla. LGS motoneurons provided recurrent facilitation to ABF, St, and FHL, while activation of Pla motoneurons produced facilitation in St, LGS, and FHL.

Contributions of different functional groups of motor nuclei to recurrent inhibition

Our data augment evidence that recurrent inhibition is produced in different amounts by different functional groups of motor nuclei. Recurrent collaterals are absent in motoneu-
FIG. 4. Examples of responses recorded in TA, EDL, and LGS motoneurons are shown in this figure. Format is same as in Fig. 2.

rons of intrinsic plantar muscles (Cullheim and Kellerth 1978) and flexor digitorum longus (McCurdy and Hamm 1992) and activation of these motor pools produces no recurrent inhibition (Fleshman et al. 1984; Hamm 1990). The present study demonstrates that although a substantial degree of recurrent inhibition is produced by the TP motor nucleus, the three peroneal motor nuclei produce only small recurrent effects and that EDL produces recurrent inhibition that is considerably smaller than that produced by TA.

One difficulty in comparing the contributions of motor nuclei is the difference in the number of motoneurons each contains, because the magnitude of composite recurrent IPSPs should increase with the number of motoneurons that are activated. This factor is considered in Fig. 6, which shows the amplitude of recurrent inhibition produced by stimulation of each muscle nerve in relation to the size of the motor nucleus. The three largest inhibitory projections from each motor nucleus are plotted as a function of the number of alpha motoneurons in the activated nucleus. For comparison, the dashed line shows the mean RIPSP amplitude expected from the product of the number of motoneurons contributing to recurrent inhibition and the average RIPSP amplitude produced by activation of individual motoneurons (McCurdy and Hamm 1994a). All of the mean RIPSP amplitudes fall below this line, indicating that each composite RIPSP is less than the sum of individual RIPSPs produced by the total number of motoneurons in each pool. This sublinear summation of RIPSPs may indicate nonlinear summation or saturation of motoneuron input at the Renshaw cell level (e.g., Hultborn et al. 1988) or possibly the effect of interactions between Renshaw cells (see DISCUSSION). Figure 6 shows that the motor nuclei most effective in producing recurrent inhibition in relation to their size are TP, TA, and St. LGS, ABF, and Pla are somewhat less effective. The RIPSPs produced by FHL, EDL, PerL, PerB, and PerT are the least effective in producing recurrent inhibition. Of these, three are involved in digit function (FHL, EDL, and PerT), two express variable patterns of activity during locomotion (PerL and PerT) and three are primarily facilitated by the activity of other motor nuclei through other recurrent pathways (PerL, PerB, and PerT). Although two of these motor nuclei have principal actions about the abduction-
adduction axis (PerL and PerB), TP, which is one of the most effective motor nuclei, also has a principal action about this axis.

**DISCUSSION**

This study demonstrated several features in the pattern of recurrent inhibitory and facilitatory projections linking motor nuclei that innervate muscles with actions at the ankle. Recurrent facilitation was widespread in our sample of recordings, contributing to more than half of the responses, and potential mechanisms underlying these responses and the significance of these projections are considered. The recurrent inhibition and facilitation received by each motor nucleus and produced by its activation was often correlated with its pattern of locomotor activity, its use in stereotyped or variable activity, or its mechanical action at the ankle or toes, but no single factor was sufficient as a basis for complete distribution of recurrent effects. Finally, we found that the recurrent inhibition produced by individual motor nuclei varied, with some making much larger contributions than others. The contribution of different motor nuclei to recurrent inhibition and facilitation are considered in relation to the function of this spinal system.

**Mechanisms and significance of recurrent facilitation**

Recurrent facilitation has been observed in previous studies in which the spinal cord was unanesthetized or only lightly anesthetized (Hamm 1990; Hultborn et al., 1971b; Illert and Wietelmann 1989; Renshaw 1941; Wilson et al. 1960). Following evidence by Wilson and Burgess (1962) that recurrent facilitation is a disinhibition, Hultborn et al. (1971b) demonstrated that most recurrent facilitation is produced by the Renshaw-mediated inhibition of tonically active Ia reciprocal inhibitory interneurons. Much of the recurrent facilitation observed in this study is consistent with this mechanism. For example, Ia reciprocal inhibition from gastrocnemius-soleus to TA and EDL is well-documented and the recurrent facilitation that is produced in TA and EDL from triceps surae (cf. Wilson et al., 1960) is readily accounted for by this mechanism. Recently, Bonasera and Nichols (1996) have demonstrated length-sensitive reciprocal inhibitory reflexes between TP and PerB, whose characteristics are consistent with Ia reciprocal inhibition. Because activation of TP produces inhibition in the homonymous and synergist motoneuron pools, facilitation from TP to PerB found in this study is likely attributable to recurrent inhibition of Ia reciprocal interneurons that receive Ia input from TP and project to PerB. Hultborn et al. (1971a) found an extended pattern of recurrent inhibition of Ia reciprocal inhibitory interneurons similar to the pattern of inhibition of motoneurons. Accordingly, motor nuclei that inhibit the TP motor nucleus (e.g., LGS, ABF, TA) should also facilitate PerB via inhibition of the Ia interneurons that project to PerB.

Other potential mechanisms of facilitation include inhibition between Renshaw cells (Ryall 1970, 1981) and direct projections of recurrent collaterals to motoneurons (Cullheim et al. 1984). Indirect evidence suggests that mutual inhibition may occur between Renshaw cells excited by the same or synergistic motoneuron pools (Ryall et al., 1972; cf. Windhorst et al., 1989). McCurdy and Hamm (1994b) observed recurrent facilitatory potentials produced in individual motoneurons by stimulation of another synergistic
individual Renshaw cells (Eccles et al. 1954, 1961b; Ryall 1981) linked by strong recurrent inhibition. The activity of EDL (see Figs. 4 and 5). This diversity is consistent with the video evidence of weak correlations between the activity of LGS and Pla (cf. Renshaw 1941; Wilson et al. 1960) and functional motor nuclei (Hamm and McCurdy 1996; Turkin and Hamm 1996). Some responses had the "wrong" sign, either flexors like TA or extensors like LG and medial gastrocnemius, depending on the pattern of activity in the bifunctional motor nuclei (Hamm and McCurdy 1996; Turkin and Hamm 1996). In contrast, preliminary observations provide evidence of weak correlations between the activity of TA and EDL (Turkin and Hamm 1996), which are not linked by strong recurrent inhibition. The activity of EDL may be altered in different forms of locomotion that further

Correlates to the distribution of recurrent inhibition

The most consistent factor associated with motor nuclei that receive and produce the largest amounts of recurrent inhibition is their participation in stereotyped patterns of locomotor activity. The TP, TA, Pla, LGS, and ABF motor nuclei all produce stereotyped patterns of locomotor activity and all figure prominently in recurrent inhibitory circuits. Conversely, the motor nuclei of PerL, PerT, and EDL exhibit variable locomotor activity and the amounts of recurrent inhibition they receive and produce after activation are considerably less than received and produced by the former group.

This association between recurrent inhibition and stereotyped locomotor activity was not found for several of the motor nuclei however. Although strong projections were found between St and TA, St has a variable pattern of locomotion. It can produce two bursts of activity, starting just before paw contact and paw lift-off, with changes in the size of these components dependent on the speed of locomotion (Engberg and Lundberg 1969; English and Weeks 1987; Smith et al. 1993). Despite this adaptive variability, evidence suggests that St receives stereotyped locomotor commands. Perret and Cabelguen (1980) demonstrated in thalamic cats that St activity during the extensor or flexor phase of fictive locomotion could be controlled by the activity of flexor reflex afferents and they argued that bifunctional motor nuclei like St receive stereotyped locomotor commands from either the extensor or flexor components of the spinal pattern generator depending on such sensory control. The possibility that St receives stereotyped locomotor commands is supported by recent studies of correlations between the activity of motor pools during fictive locomotion. These studies, in which neurogram activity was analyzed in the frequency domain to determine the presence of locomotor signals shared by different motor nuclei, demonstrated correlations between St (or St and posterior biceps femoris) and either flexors like TA or extensors like LG and medial gastrocnemius, depending on the pattern of activity in the bifunctional motor nuclei (Hamm and McCurdy 1996; Turkin and Hamm 1996). In contrast, preliminary observations provide evidence of weak correlations between the activity of TA and EDL (Turkin and Hamm 1996), which are not linked by strong recurrent inhibition. The activity of EDL may be altered in different forms of locomotion that further...
distinguish it from TA activity (Trank et al. 1996; Trank and Smith 1995). These data support the hypothesis that the motor nuclei comprising a set that receive recurrent inhibition from one another are those that receive the same commands during activities like locomotion.

The pattern of inhibition and facilitation for the PerB motor nucleus is an important exception to the correlation between patterns of locomotor activity and recurrent inhibition. PerB exhibits regular stance phase activity during locomotion (Abraham and Loeb 1985; Loeb 1993); yet, it receives practically no recurrent inhibition from other motor nuclei with regular stance phase activity. Instead, PerB receives recurrent facilitation from these sources. PerB acts primarily as an abductor in direct opposition to TP, and Bonasera and Nichols (1996) have demonstrated that TP and PerB are linked by mutually inhibitory length dependent reflexes. These findings suggest that the mechanical and reflex antagonism between TP and PerB excludes the latter from the set of motor nuclei active in stance that are subject to recurrent inhibition from each other during activity.

The data on TP and TA provide an additional correlate between mechanical action and the distribution of recurrent inhibition. Both TA and TP adduct the ankle, at least in abducted ankle positions. The inhibition between TA and TP is not large, but it is similar in magnitude to the inhibition from TA to EDL. The significance of these projections is not clear. Because TP and TA activity have not been observed during the same phase of locomotion, the inhibition produced by one should have no effect on the activity of the other. It remains to be seen whether or not these two motor nuclei may be simultaneously active in forms of locomotion in which the patterns of activity have not been reported, such as in turning movements.

On the whole, the results of the present study support the observation that the extended pattern of recurrent inhibition correlates with the pattern of activity of motor nuclei during stereotyped activities like locomotion, as argued previously (Hamm 1990). However, although the extended pattern includes motor nuclei that lack a common mechanical action, our results also suggest that the mechanical action of individual muscles is a factor in the distribution of recurrent inhibition. The control of posture and locomotion requires the production of torques about the abduction-adduction and inversion-eversion axes of the ankle, in addition to flexor and extensor torques. The partial correlation between the organization of recurrent inhibition in motor nuclei of ankle muscles and their mechanical actions suggests that recurrent inhibition is involved in the control of actions outside the sagittal plane.

**Contribution of different motoneuron pools to recurrent inhibition and facilitation**

Motor nuclei that innervate hindlimb muscles of the cat do not contribute uniformly to recurrent projections in relation to their size. Projections were particularly weak from PerL, PerB, EDL, and FHL. This weakness may be related to the size of the recurrent collateral arbors of motoneurons in these pools, as seems to be the case with FHL (McCurdy and Hamm 1992). McCurdy and Hamm (1992) noted a gradient in the complexity of recurrent collaterals that seemed to be correlated with action at the digits and individualized patterns of use. This observation is consistent with the digit functions of EDL, FHL, and PerT, and with observations of variable activity in EDL (Trank et al. 1996; Trank and Smith 1995) and PerL (Hensbergen and Kernels 1992; Loeb 1993), which suggest that these muscles are used in an individualized manner. But the weak recurrent effects produced by PerB suggest that other factors than digit function and individualized use may influence the participation of a motor pool in recurrent inhibition.

PerB neither acts at the digits nor does it produce individualized patterns of activity. However, the function of recurrent inhibition appears dependent on participation of several motor pools in a common task. This statement is based on the extended pattern of recurrent inhibition and its correlation with patterns of activity during locomotion, in which many pools are simultaneously active. It also stems from estimates of strength between individual pools, which in this and previous studies, have suggested that recurrent inhibition from individual pools would produce negligible effects. From determination of the effective synaptic current produced by a single motoneuron pool, Lindsay and Binder (1991) estimated that recurrent inhibition would have little influence on the discharge rate of a motoneuron. However, McCurdy and Hamm (1994a) estimated that recurrent inhibition produced by several motoneuron pools could alter force development of recently recruited motor units by 25%. Although these estimates were based on studies in which fast, large-diameter motor axons were activated with slower, small-diameter motor axons, studies in both cat (Hultborn et al. 1988) and human (Bussel and Pierrot-Deseilligny 1977) indicate that the recruitment of smaller motor units effectively contributes to the activation of Renshaw cells and the production of recurrent inhibition.

Reciprocal inhibition thus appears to be dependent on the activity of multiple pools to achieve any such modulating effect in the activity of motoneurons, although its strength is sufficient to decorrelate the discharge of motoneurons within individual pools (Maltenfort et al. 1995). Although PerB is coactive with several other motor nuclei during stance, its mechanical action and reflex organization put its function in opposition to other motor nuclei active in this group. We suggest that this distinction isolates PerB from the recurrent pathways in which other motor nuclei active in stance participate. Such motor nuclei acting individually through recurrent circuits would not significantly affect the level of motoneuron activity. On the other hand, motor nuclei acting together during stereotyped activities like locomotion should generate sufficient activity in recurrent circuits to modulate the level of activity in active motoneuron pools and their associated sets of IA reciprocal inhibitory interneurons.

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