

Interlimb coordination during fictive locomotion in the thalamic cat

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Summary. Efferent discharges in muscle nerves of the four limbs were recorded simultaneously during spontaneous fictive locomotion in thalamic cats with the goal of understanding how the central nervous system controls interlimb coordination during stepping. The onset of the bursts of activity in the nerve of a selected flexor muscle in each limb allowed the temporal and the phase relationships between the fictive step cycle of a pair of limbs to be determined. Our main results are the following: 1) the fictive step cycles of the two forelimbs are always strictly alternated whereas the phasing of the step cycles of either the two hindlimbs or pairs of homolateral or diagonal limbs is more variable; 2) the time interval between the onsets of the flexor bursts of one of the two pairs of diagonal limbs is independent of the step cycle duration; 3) distinct patterns of interlimb coordination exist during fictive locomotion; a small number of patterns of coordination involving all four limbs, which correspond to the walking and the trotting gaits in the intact cat, occur very frequently. The results demonstrate that the central nervous system deprived of phasic afferent inputs from the periphery has the capacity to generate most of the patterns of interlimb coordination which occur during real locomotion. They further support the view that the central pattern of interlimb coordination essentially results from diagonal interactions between a forelimb generator for locomotion and a hindlimb one.

Key words: Locomotion – Interlimb coordination – Cat

Introduction

Numerous studies in mammals have provided evidence that the central nervous system deprived of phasic afferent feedback from the periphery can generate the complex pattern of activations of the various muscle groups of a

single limb occurring during locomotion (intralimb coordination) (see Grillner 1981 for review).

In addition, some results suggest that there is also central control of the coordination of step cycles of homologous limbs. Indeed, during fictive locomotion, patterns of coupling of fore- or hind- limbs comparable to those observed during true locomotion have been observed in the thalamic cat (Perret 1976) and in the spinal cat (Grillner and Zangger 1979; Kniffki et al. 1981; Zangger 1981; Koehler et al. 1984; see also Viala and Buser 1969; Viala and Vidal 1978 in the rabbit).

In contrast, little information is available about the ability of the central nervous system to control coordination of all four limbs during stepping (interlimb coordination). Interlimb coordination has been briefly mentioned during DOPA-induced fictive locomotion in the high spinal cat injected with 4-aminopyridine (Zangger 1981; see also Viala and Vidal 1978 in the rabbit).

Such knowledge is nevertheless a prerequisite to the study of the role of supraspinal or propriospinal neurons during locomotion since the discharge pattern of some of these cells appears to be better related to interlimb coordination rather than to intralimb coordination (see e.g. Drew et al. 1986).

The present paper deals with interlimb coordination during fictive locomotion in the thalamic cat. Our results indicate that different forms of interlimb coordination, involving a diagonal coupling between forelimbs and hindlimbs, do exist during the fictive locomotion.

Some of the results have been briefly published elsewhere (Cabelguen et al. 1981; Orsal et al. 1988b).

Methods

The experiments were performed on 20 adult cats (2.5–3 kg). Under short lasting anaesthesia (Brietal 10 mg/kg i.v.), a tracheotomy was performed and a cannula inserted into the left jugular vein for injection of drugs and fluids. The cat was then rigidly mounted in a frame that fixed the head and the lumbar spine. After a bilateral craniotomy, the whole cerebral cortex and all brain tissue rostral to A 10 Horsley-Clarke plane were removed by suction (Orlovsky and Feldman 1972; Perret and Cabelguen 1980). The animal was then paralyzed with gallamine triethiodide (Flaxedil 20 mg/kg i.v. repeated when needed) and artificially ventilated. Body temperature was kept near 38°C by means of a radiant heat lamp.

Abbreviations: CD step cycle duration, LF left forelimb, LH left hindlimb, m slope of correlation curve, N number of step cycles, r correlation coefficient, RF right forelimb, RH right hindlimb, Ti time interval

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In each hindlimb, the nerve to sartorius (lateral and medial parts) or tibialis anterior and, in each forelimb, the nerve to trapezius, biceps brachii or brachialis, were dissected free, cut and covered with warm paraffin oil. Their central stumps were mounted on silver bipolar electrodes for recording.

After recovery from anaesthesia, spontaneous locomotor-like activities could be recorded from hindlimb (Perret 1976) and forelimb (Cabelguen et al. 1981) muscle nerves (fictive locomotion). It should be noted that all the muscle nerves selected in the present study display a characteristic flexor pattern of activity during fictive locomotion (Perret and Cabelguen 1980; Cabelguen et al. 1981). However, during actual locomotion in the thalamic (Perret 1983) or normal cats (Hoffer et al. 1987) some of these muscles can exhibit an additional extensor e.m.g. burst (see Orsal et al. 1986 for further discussion).

Nerves to hip, ankle, scapula and elbow flexor muscles were chosen in the present study on interlimb coordination because: (i) they are monophasically active during the fictive step cycle, in contrast to nerves to knee and shoulder flexor muscles ("bifunctional muscles") (Perret and Cabelguen 1980; Cabelguen et al. 1981); (ii) the onset of the locomotor bursts in all of the flexor muscle nerves of a limb can be considered as synchronous and taken as the onset of the step cycle, whereas in extensor muscle nerves it shows greater variability (Perret 1983). Therefore, the duration of the step cycle of a limb can be reliably estimated as the interval between the onsets of two successive bursts of activity in a single flexor muscle nerve of that limb. (iii) the temporal relationship between the locomotor discharges of flexor muscle nerves and the flexor phase of the step cycle or the limb movement shows little variation (see Perret 1983). Therefore, monitoring of the flexor bursts in each of the four limbs during stepping can be used to determine the temporal spacing of step cycle of all the different limbs (i.e. interlimb coordination).

Recording and analysis

The electroneurograms were amplified using AC-coupled amplifiers (bandwidth: 150Hz-20KHz) and displayed on a Siemens Oscillomink paper recorder (linear response: 0-1200 Hz). Data were simultaneously stored on a 7-channel magnetic tape recorder for subsequent analysis.

For each limb, the times of onset and termination of the flexor bursts were measured on polygraphic records using a digitizing tablet connected to a microcomputer Apple II (final resolution: 4.3 ms per point). The onsets and the offsets of the flexor bursts were sorted using visual estimation of the level of the noise in the eng records at rest.

The method for determining the temporal relationship between fictive step cycles of any two different limbs was essentially the same as that used by English (1979). Briefly, the time interval between the onsets of the flexor bursts of the two limbs were measured and a phase interval, expressed in degrees, was calculated by dividing this time interval by the duration of the step cycle of the first limb used in the determination (the "reference limb") (see Fig. 1A). Thus, a phase interval of 0 or 360° corresponds to in-phase fictive step cycles and a phase interval of 180° to strict alternating ones. It is worth noting that this method assumes that the duration of the step cycle is the same when determined at each of the four limbs. In order to evaluate the validity of this assumption a linear regression analysis between the step cycle durations of the different limbs was first performed.

The phase interval was determined between fictive step cycles of homologous (i.e. the two forelimbs or the two hindlimbs), homolateral (i.e. the forelimb and the hindlimb on the same side of the body) and diagonal limbs and, for each pair of limbs, a circular plot of the phase interval (circumference) versus the locomotor frequency (1/cycle duration of the corresponding fictive step cycle) (radii) and an histogram representing the number of fictive step cycles (ordinate) with which a particular phase interval (abscissa) was encountered, were constructed.

Results

In the paralyzed thalamic cat, well-organized rhythmic motor activity could be recorded in the flexor nerves to both forelimbs and hindlimbs (fictive locomotion).

Figure 1A illustrates the motor pattern which was observed in more than 70% of the recordings of fictive locomotion. It consisted of out-of-phase activations of the flexor nerves of homologous limbs (LF-RF and LH-RH in Fig. 1A) and of in-phase activations of the flexor nerves of diagonal limbs (LF-RH and RF-LH in Fig. 1A). This motor pattern could last unchanged for long periods. For example, in the experiment illustrated in the Fig. 1A it was very stable for nearly an hour.

The other motor patterns which were sometimes observed resulted from a change in the phase relation between the flexor bursts of the two hindlimbs, the flexor bursts of the two forelimbs being always in strict alternation.

As an example, Fig. 1B shows a period of fictive locomotion during which the phase relation between the flexor bursts of the hindlimbs (RH-LH) changed spontaneously from an out-of-phase relation (left side of Fig. 1B) to an in-phase one (right side of Fig. 1B); the strict alternating activity in the two forelimb flexor nerves being unchanged

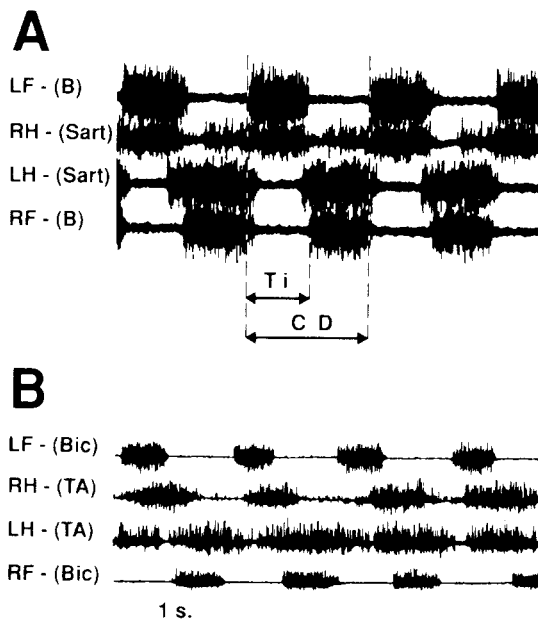


Fig. 1A, B. Interlimb coordination during fictive locomotion in the thalamic cat. In both **A** and **B**, from top to bottom, recordings from flexor muscle nerves of the left forelimb (LF), right hindlimb (RH), left hindlimb (LH) and right forelimb (RF). **B:** brachialis. TA: tibialis anterior. Sart: sartorius (medial and lateral parts). Bic: biceps brachii. **A** Note alternated pattern in homologous limbs (LF-RF; LH-RH) and in-phase pattern in diagonal limbs (LF-RH; LH-RF). **B** Note, from left to right, change in phase relationship between flexor bursts in LH and in the three other limbs. An example of the parameters measured is indicated in **A**. CD: duration of the LF step cycle. Ti: time interval between onset of LF and RF flexor bursts. The ratio Ti to CD was calculated and expressed in degrees for each step cycle (phase interval). See text for details. The time calibration is valid for both **A**, **B**

during that time. Note that the relatively abrupt switch from out-of-phase to in-phase pattern in hindlimbs was not accompanied by any significant change in the duration of the fictive locomotor cycle. If one now considers the change in the coordination pattern of the all four limbs illustrated in Fig. 1B, it appears as resulting only from the change in the time of occurrence of the flexor bursts of the left hindlimb (LH), since the phase relations between the flexor bursts of the three other limbs (LF-RH-RF) remain nearly invariant.

A salient observation in our experiments was a clear cut shaping of the flexor bursts in the two forelimbs and one of the hindlimbs (LF-RF-LH in Fig. 1A; LH-LF-RH in Fig. 1B). In contrast the neurogram profile of the remaining hindlimb was smoother, consisting of flexor

bursts separated by short periods of inactivity (Fig. 1A: RH; Fig. 1B: LH).

1. Step cycle duration

In Fig. 2, each graph displays linear regressions relating the step cycle durations of two different limbs in one experiment in which spontaneous variations of the locomotor rhythm occurred. The number of step cycles (N), the correlation coefficient (r) and the slope (m) of each linear regression are indicated close to each graph.

The regression analysis indicates a strong correlation between the step cycle durations of homologous limbs (Fig. 2A: LF-RF, $r=0.88$; Fig. 2B: LH-RH, $r=0.72$),

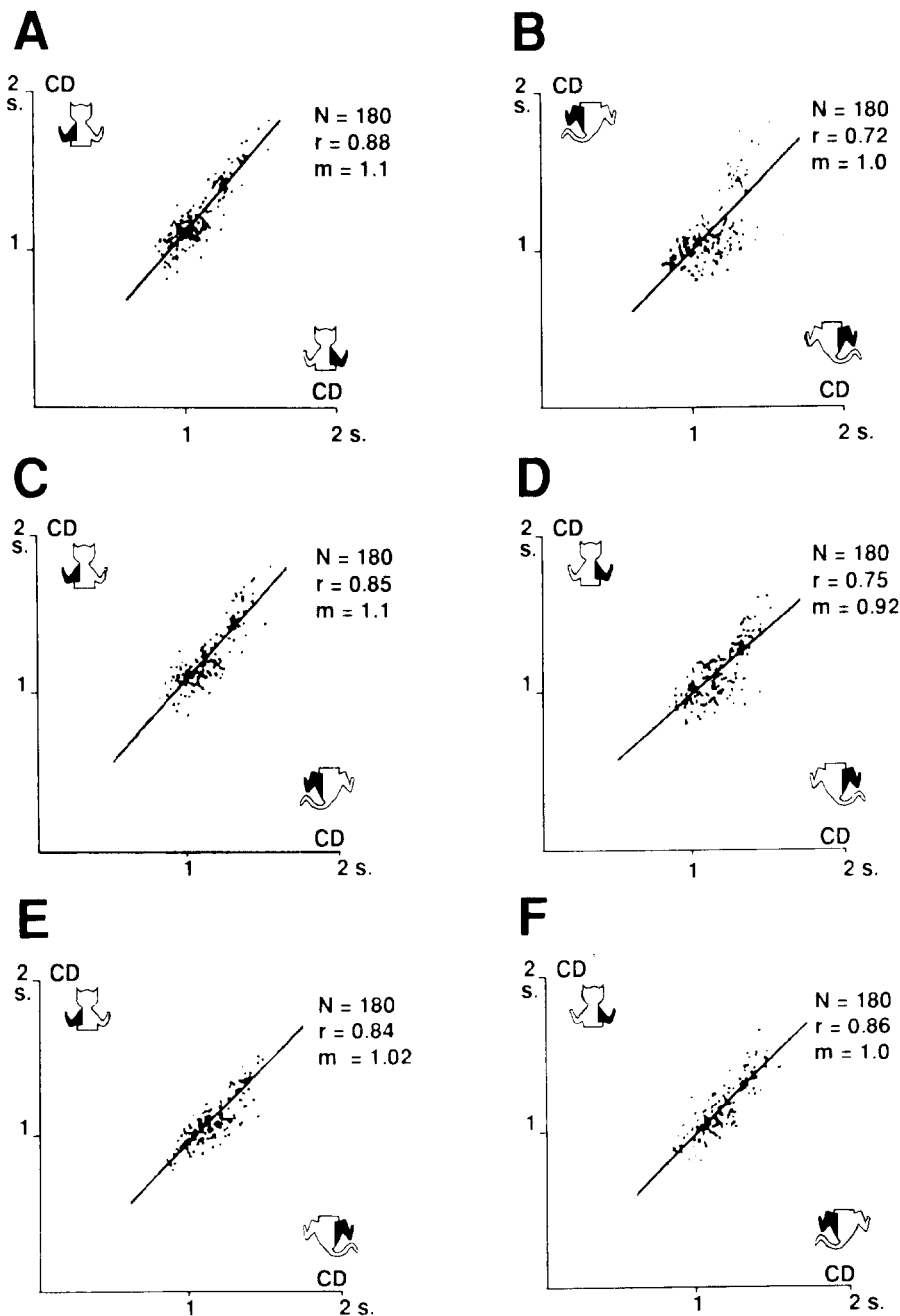


Fig. 2A-F. Relationship between the duration of the step cycle of the four limbs. In each graph, each regression line relates the cycle duration in two limbs (indicated in this figure and the subsequent ones as filled areas in inserts near axis). Number of step cycles (N), correlation coefficients (r) and slopes of regression lines (m) are indicated close to each graph. Data from the same experiment

homolateral limbs (Fig. 2C: LF-LH, $r=0.85$; Fig. 2D: RF-RH, $r=0.75$) and diagonal limbs (Fig. 2E: LF-RH, $r=0.84$; Fig. 2F: RF-LH, $r=0.86$). The relatively weaker correlation in the case of the two hindlimbs (Fig. 2B) could be partly related to the greater uncertainty in the determination of the onset of hindlimb flexor bursts which are often less clear cut than forelimb flexor bursts (see above).

Moreover, the six graphs of Fig. 2 show remarkably similar regression curves. Indeed, relationships between the cycle durations of homologous limbs (Fig. 2A and 2B), homolateral limbs (Fig. 2C and 2D) and diagonal limbs (Fig. 2E and 2F) all show slopes close to 1.

These results indicate that the duration of the step cycle is the same when measured at each of the different limbs (mean duration 1.13 ± 0.29 s in the experiment illus-

trated in Fig. 2). Therefore, an analysis of interlimb stepping pattern with circular plots (see Methods) could be performed.

2. Time interval analysis

In an attempt to determine significant time events in the interlimb coordination during fictive locomotion we have measured the time interval between the onsets of the flexor bursts of two different limbs and study its variations with respect to step cycle duration.

Figure 3 illustrates the six dispersion diagrams obtained in a typical experiment. The regression analysis reveals a good correlation in the case of the two forelimbs

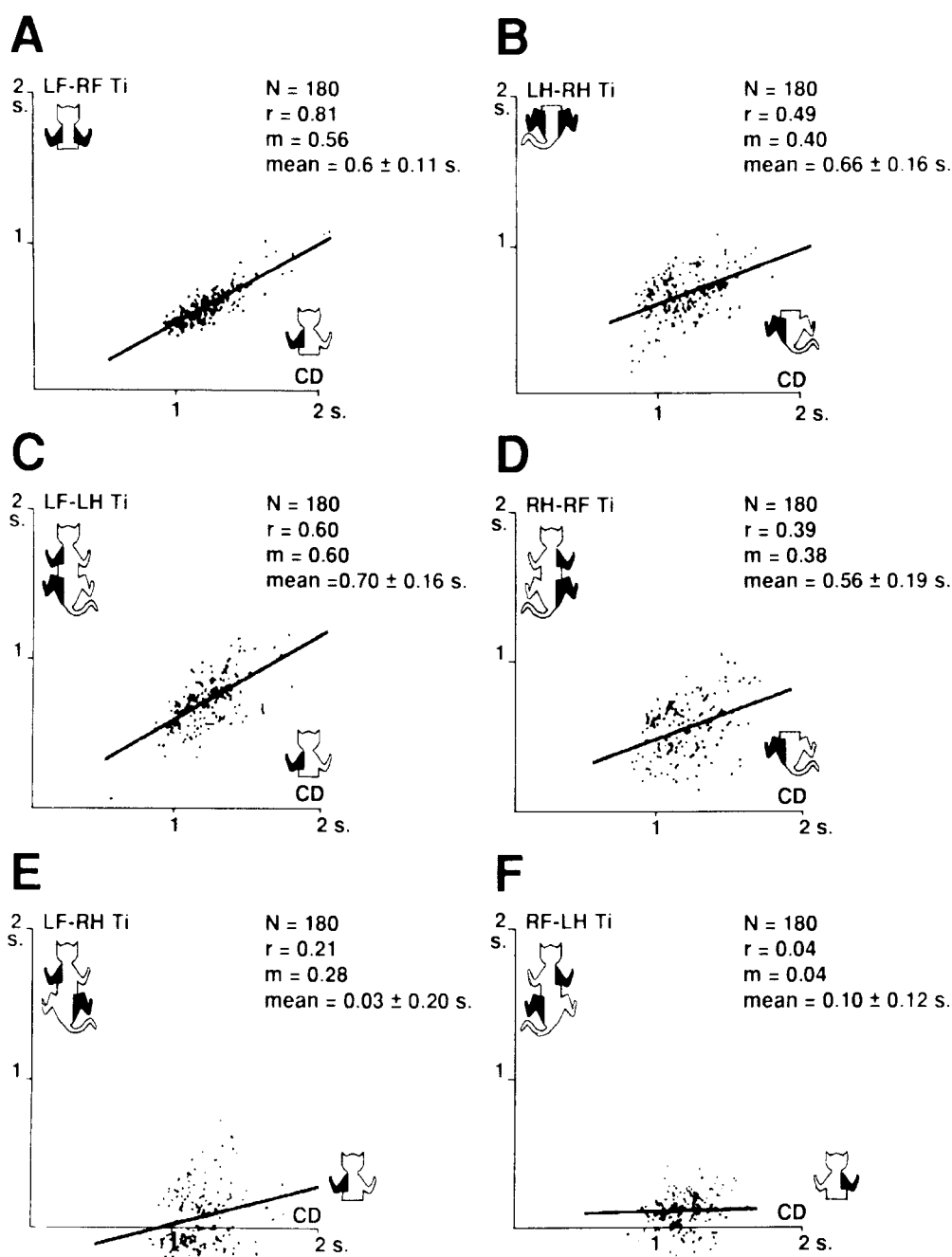


Fig. 3A-F. Interlimb relationship between onsets of flexor bursts in pairs of limbs during fictive locomotion of the thalamic cat (same experiment in A-F). In each graph, each regression line relates time interval (T_i) between onsets of flexor bursts of two limbs (ordinate) to the step cycle duration (abscissa). Number of step cycles (N), correlation coefficients (r), slopes of the regression lines (m) and mean values \pm S.D. of T_i are indicated close to each graph

(Fig. 3A, $r=0.81$) and a relatively weaker, but significant one, in the case of the two hindlimbs (Fig. 3B, $r=0.49$). The less reliable estimation of the onset of some of the hindlimb flexor bursts might explain, partly at least, the weaker correlation found in the case of hindlimbs.

The regression analysis also shows a correlation of the time interval between flexor bursts of homolateral limbs with the step cycle duration, this correlation being weaker for one pair of homolateral limbs (RH-RF, $r=0.39$ in Fig. 3D) than for the other pair (LF-LH, $r=0.60$ in Fig. 3C). In contrast, the time interval between flexor bursts of diagonal limbs was not correlated with the step cycle duration (Fig. 3E, $r=0.21$; Fig. 3F, $r=0.04$). In addition, note that the slope of the regression curve of one pair of diagonal limbs (RF-LH, Fig. 3F) is close to 0 ($m=0.04$). This indicates that the flexor burst of one limb tends to occur at a fixed time (0.1 ± 0.12 s in Fig. 3F) in relation to the onset of the flexor burst of the relevant diagonal limb.

The time intervals of homologous (Fig. 3A and Fig. 3B) and homolateral (Fig. 3C and Fig. 3D) limbs always lie in one restricted part of the plot (above or below the horizontal axis, depending on the reference limb used). In contrast, for diagonal limbs, both positive and negative time intervals were found at a given step cycle duration (Fig. 3E and Fig. 3F). These results indicate that for a pair of homologous or homolateral limbs the order of the times of occurrence of flexor bursts was independent of the step cycle duration whereas it could vary for a pair of diagonal limbs.

3. Phase interval analysis

A detailed analysis of the phase relationship between the step cycles of different limbs has been made by constructing circular plots representing the locomotor frequency (radii) vs the phase interval between the locomotor cycles of two different limbs (circumference).

Figure 4 illustrates the circular plots constructed from the data of a typical experiment in which spontaneous variations in the interlimb coordination pattern occurred. In each display, the phase interval increases in a counter-clockwise direction from three o'clock (0° or 360°), the locomotor frequency increases from the center out and each point represents a phase interval derived from a single step cycle.

The circular plot in Fig. 4A shows that the phase intervals between flexor bursts of the two forelimbs are aggregated near 180° . This suggests that the type of coordination of forelimb step cycles during fictive locomotion is frequently a strict alternation whatever the locomotor frequency is. Moreover, the absence of phase values on the right of the vertical axis of the radial plot strongly suggests that in this walking preparation forms of coordination close to in-phase mode never occur in forelimbs.

Plotting the phase intervals (abscissa) against the frequency with which they were observed (ordinate) (Fig. 5A) shows that the phase intervals are grouped around 180° , with a narrow dispersion ($184.6 \pm 40^\circ$). Note

that the dispersion observed in the experiment illustrated in fig. 5A was the widest observed in the experiments.

Figure 4B shows the circular plot obtained for the two hindlimbs. Although the phase intervals are scattered throughout the circular plot, most of them lay in the left side of the plot ($180 \pm 90^\circ$). This indicates a predominance of out-of-phase forms of hindlimb coordination during fictive locomotion. However, on the right of the radial plot ($0 \pm 90^\circ$), a few phase intervals representing in-phase forms of hindlimb coordination were also found. Note the absence of clear correlation between the phase intervals in a region of the plots and the locomotor frequency.

The frequency histogram of Fig. 5B shows clearly that the phase intervals encountered in this experiment were distributed into two main subpopulations: the first one grouped about 180° and the second, smaller one, about 270° . The few phase intervals corresponding to the in-phase forms of hindlimb coordination are represented at the ends of the frequency histogram.

This double-peak distribution of the phase intervals between hindlimb flexor bursts during fictive locomotion was not found in all experiments. Indeed, in some cats, the distribution of phase interval showed a single peak either around 180° (Fig. 5C) or around 270° (Fig. 5D) or its mirror image at 90° (Fig. 5E). The absence of peak in the in-phase range ($0 \pm 90^\circ$) probably resulted from the absence of long periods of stable in-phase relations.

These results indicate that during fictive locomotion hindlimbs are frequently coupled in either strict alternation (180°) or with a phase interval of 270° (or its mirror image 90°).

The circular plots obtained for the left (Fig. 4C) and the right (Fig. 4D) homolateral limbs are very comparable. Most of the phase intervals are scattered in the $180 \pm 90^\circ$ range, thus indicating frequent out-of-phase forms of coordination between homolateral limbs during fictive locomotion. Phase intervals in the $0 \pm 90^\circ$ range, which correspond to in-phase forms of coordination, were encountered less frequently. Again, there is no clear correlation between a phase interval range and a particular locomotor frequency.

The frequency histograms further show that in this experiment the phase intervals between flexor bursts of a pair of homolateral limbs were more or less broadly distributed throughout the $180 \pm 90^\circ$ range, with two more or less distinct peaks (Fig. 6A: around 150° and 210°). However, in other experiments, the phase intervals were closely grouped around a single value (Fig. 6B: 250° ; Fig. 6C: 150° ; Fig. 6D: 190°). These results indicate that the out-of-phase coupling of homolateral limbs during fictive locomotion can follow several different phase interval combinations.

An example of the circular plots obtained for diagonal limbs is illustrated in Fig. 4E (LF-RH) and in Fig. 4F (RF-LH). For the two pairs of diagonal limbs, most of the phase intervals lay in the right part ($0 \pm 90^\circ$) of the radial plots. This indicates that more or less in-phase forms of coordination of diagonal limbs occur frequently during fictive locomotion. Very few phase intervals were found in the region of the plots ($180 \pm 90^\circ$) which represents out-of-phase forms of coordination between diagonal limbs.

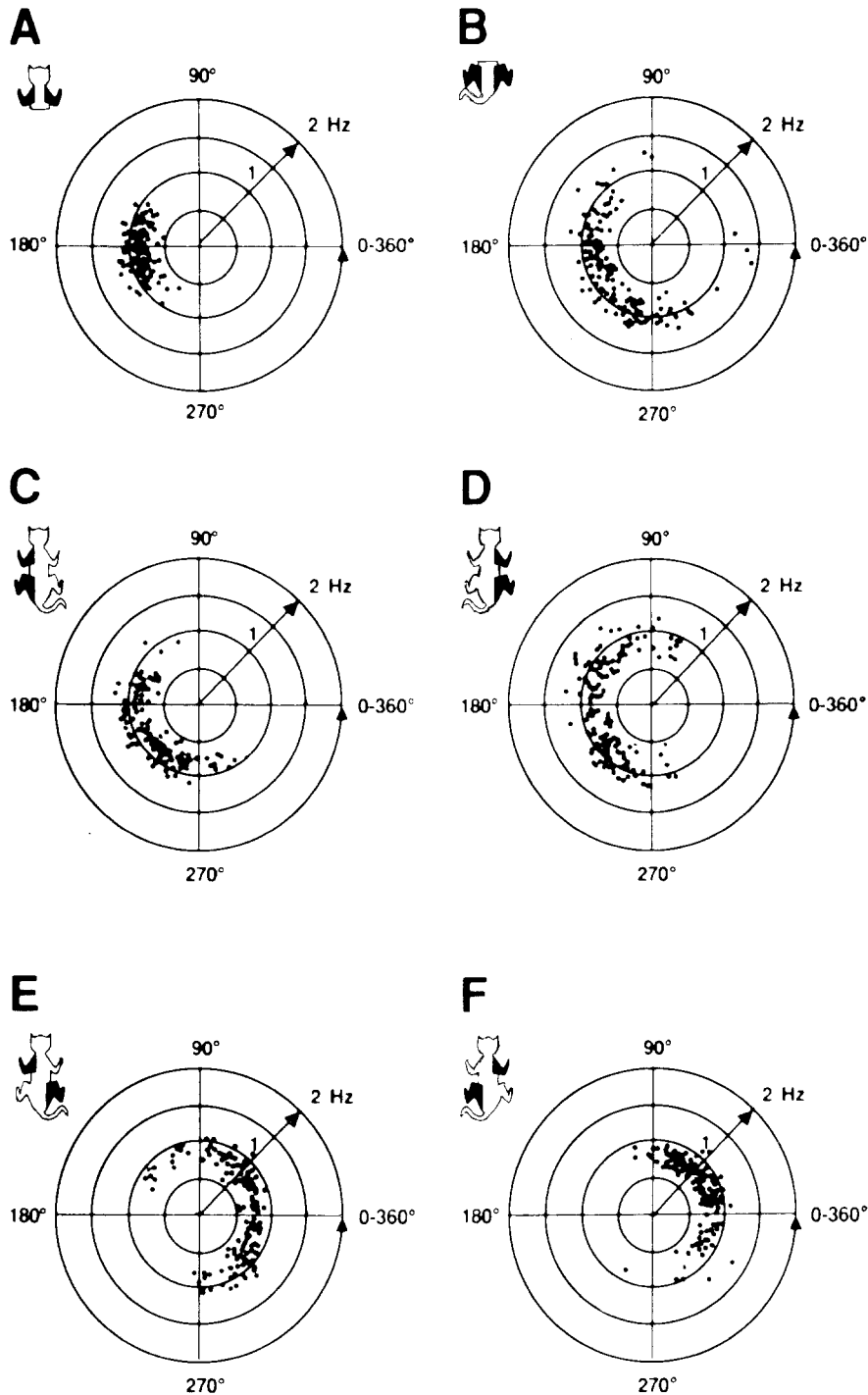


Fig. 4A–F. Patterns of interlimb coordination during fictive locomotion in the thalamic cat (same experiment as in Fig. 3). Circular plots of the locomotor frequency (radii) vs phase interval (circumference) are shown for the forelimb pair (A), the hindlimb pair (B), the left (C), and the right homolateral pairs of limbs (D), and the two diagonal pairs of limbs (E LF-RH; F RF-LH). See text for details

Again, note the absence of correlation between a particular phase interval range and the locomotor frequency.

The frequency histograms further show that in this experiment the phase intervals between flexor bursts of a pair of diagonal limbs were widely dispersed throughout the $0 \pm 90^\circ$ range, with two more or less distinct peaks (Fig. 7A: around 30° and 210°). A double-peak pattern, but with different peak values, was found in other experiments (Fig. 7B: around 270° and 330°). In contrast, in some experiments, phase intervals were strongly grouped around a single value (Fig. 7C: 80° ; Fig. 7D: 70°). These results indicate that the variety of phase intervals between

flexor bursts of diagonal limbs in the in-phase range is wide.

Discussion

1. Patterns of interlimb coordination

The results of the present study show that definite patterns of coordination of step cycles of the four limbs do exist during fictive locomotion in the thalamic cat.

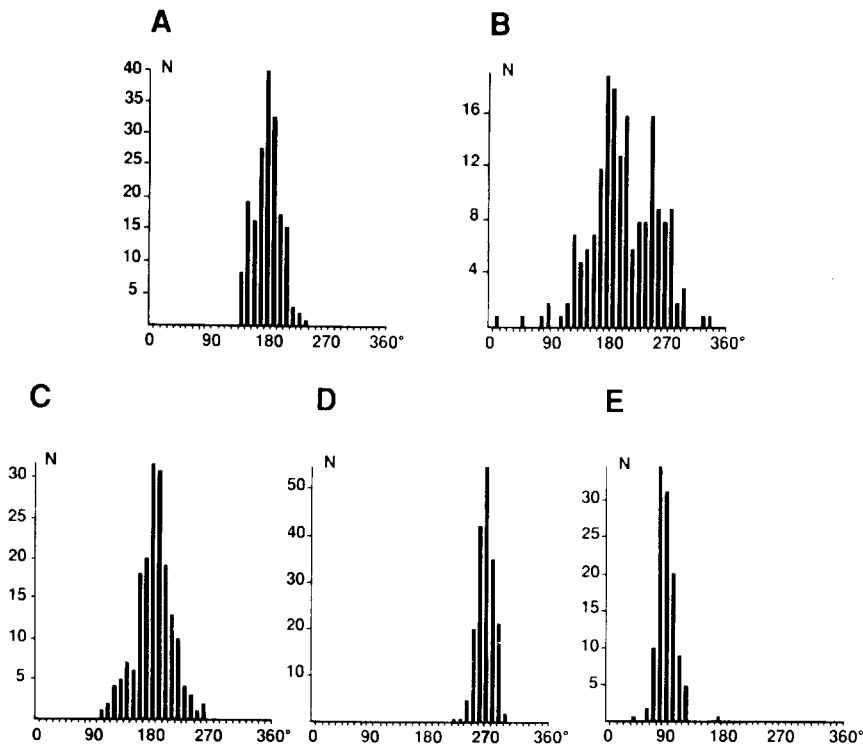


Fig. 5A-E. Histograms of phase intervals between flexor bursts in a pair of homologous limbs during fictive locomotion. Forelimb pair (**A**) and hindlimb pair (**B-E**). In this and the two subsequent figures, each histogram plots the phase interval on the abscissa (bin width: 10°) and the frequency of occurrence on the ordinate. See text for details. **A, B** Same experiments. **C-E** Three other experiments

Indeed, step cycles of the two forelimbs are tightly coupled in a strict alternation (180°) and those of the two hindlimbs are coordinated either via two well defined forms of coupling (180° , 270° or its mirror image 90°) or several possible, although less frequent, in-phase forms. Moreover, step cycles of a pair of homolateral limbs are commonly coupled in an alternated form, but relatively less frequent in-phase forms of coupling may exist. For the coordination of step cycles of a pair of diagonal limbs, in-phase patterns are very frequent, although alternated forms of coupling may occur.

The most common patterns of coordination of the fictive step cycles of all four limbs observed in the present study are very similar to those which occur during "alternate" stepping in the intact cat, i.e. during stepping in which hindlimb step cycles are out-of-phase in the $180 \pm 90^\circ$ range (e.g. walking or trotting) (Miller and van der Burg 1973; Stuart et al. 1973; Miller et al. 1975a,b; Halbertsma et al. 1976; English 1979).

On the other hand, the small number of phase intervals between fictive step cycles of the two hindlimbs in the $0 \pm 90^\circ$ range can be related to "in-phase" stepping which sometimes occurs in the intact cat (Miller and van der Burg 1973; Stuart et al. 1973; Miller et al. 1975a,b; Halbertsma et al. 1976; English 1979; English and Lennard 1982). However, the phasing of the step cycles of the two forelimbs during in-phase stepping in the intact cat (i.e. about 90° or 270°) was never observed during fictive locomotion in the thalamic cat (see however Viala and Vidal 1978 in the high spinal rabbit). On the other hand, rhythmic motor activity, in-phase coordinated between the two forelimbs, has been reported after addition of 4-AP to high spinal cats showing DOPA-induced fictive locomotion (Zangger 1981). However, it seems unlikely that

the rhythmic nervous discharges observed in this preparation are only related to locomotion (see Dubuc et al. 1986 for further discussion) and no safe conclusion about the capacity of the cat central nervous system to generate an in-phase coupling of two forelimbs can be drawn from these experiments.

Regular in-phase stepping in intact cats occurs more frequently at speeds above 3 m/s, i.e. for step cycle durations below approximately 400 ms (Goslow et al. 1973; Halbertsma 1983), while the duration of the fictive step cycles in the thalamic cat, is always above 450 ms (Perret and Cabelguen 1980; see also Dubuc et al. 1988). This can be related to the small number of observations of periods of in-phase fictive stepping in the present study and consequently to the low frequency of phase intervals in the $0 \pm 90^\circ$ range.

In conclusion, it seems reasonable to assume that the central nervous system deprived of phasic inputs coming from the moving limbs can generate most of the patterns of interlimb coordination which can occur during locomotion. In our experimental situation, a contribution of the afferents rhythmically activated by the artificial respiratory movements to interlimb coordination during fictive locomotion is excluded since different patterns of interlimb coordination and different step cycle durations were observed in spite of a constant respiratory rate (20/mn) (see also Koehler et al. 1984).

A considerable variability in interlimb stepping patterns has been pointed out in studies of limb movements and footfall patterns in intact cats (Stuart et al. 1973; Gambaryan 1974; Wetzel et al. 1975; Hildebrand 1976). In the present study, the data were pooled without distinction between fictive stepping modes (i.e. alternate versus in-phase) and the transitions between them. Therefore, as

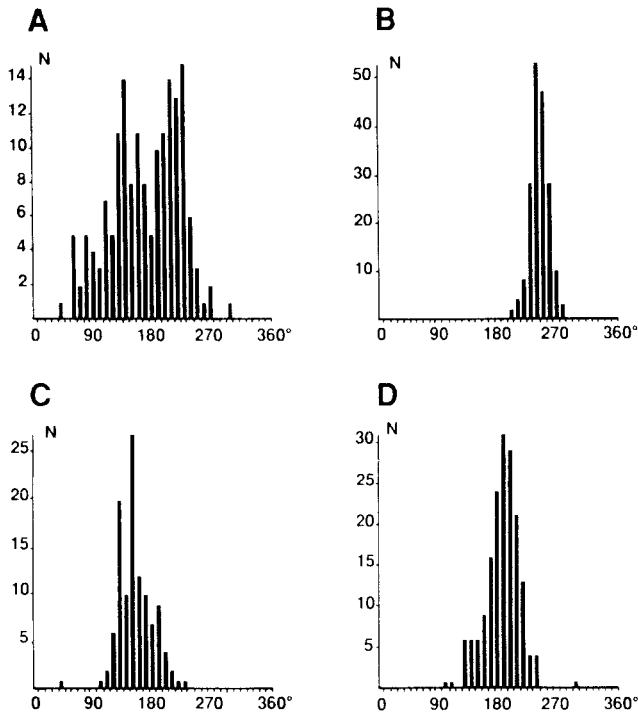


Fig. 6A–D. Histograms of phase intervals between flexor bursts in a pair of homolateral limbs during fictive locomotion. Same representation as in Fig. 5. See text for details. **A** Same experiment as in Fig. 5A, **B–D** From three different experiments

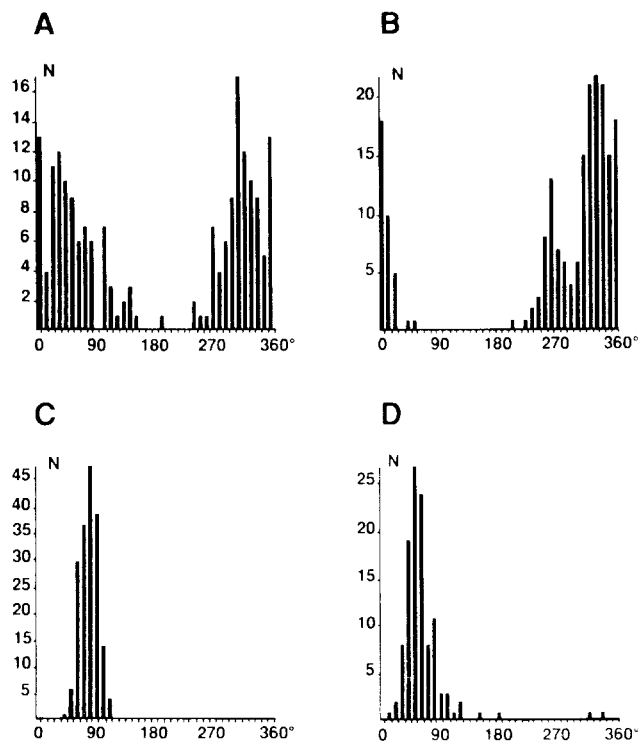


Fig. 7A–D. Histograms of phase intervals between flexor bursts in a pair of diagonal limbs during fictive locomotion. Same representation as in Fig. 5. See text for details. **A** Same experiment as in Fig. 5A, **B–D** From three different experiments.

pointed out by others (English and Lennard 1982; Halbertsma 1983), this technique increases the variability in the interlimb coordination patterns during locomotion. In addition, since stable in-phase fictive stepping occurred only during short periods, the corresponding preferred interval values were difficult to distinguish in the frequency histograms of the present study. However, the variability during fictive locomotion is not so large since phase intervals are not distributed entirely at random, preferred phase interval values exist, especially for homologous limbs (see above). It is worth noting that the preferred phase interval values found in the present study fit well with the “basic patterns” described by Miller and colleagues (Miller et al. 1975b; Halbertsma et al. 1976) for overground stepping in intact cats.

2. Time and phase constraints for interlimb coordination

The present data provide evidence for two constraints on interlimb coordination during fictive locomotion. Indeed, both the phase interval between the fictive step cycles of the two forelimbs and the time interval between the onsets of the flexor bursts of one of the two pairs of diagonal limbs may be considered as independent of the duration of the fictive step cycle. Note, however, that the pair of diagonal limbs which is time-locked could change from one experiment to the other and, in a given experiment, from one period of locomotor activity to the other.

A fixed time interval between certain kinematic events within the step cycles of a pair of diagonal limbs has not been observed in stepping intact cats (Halbertsma 1983). On the other hand, a nearly constant time interval (25–100 ms) between the onset of the first extension phase (E1) of the knee and the onset of the flexion phase (F) of the homolateral elbow has been reported in intact cats moving faster than approximately 1 m/s (Miller et al. 1975a; Halbertsma et al. 1976; see however Halbertsma 1983). A time-locking of the emgs of the appropriate hindlimb and forelimb muscles has also been found (Miller et al. 1975a). However, since the time interval values measured during actual locomotion depend on both the environmental conditions (e.g. overground versus treadmill) and the training procedures (Wetzel et al. 1975; Lockard et al. 1976), the discrepancy with the present data may result in some way from suppression of the movement-related afferent inputs in the thalamic paralyzed cat. In addition, the neural coupling of limb movements is probably reflected differently in neurographic events (e.g. onsets of flexor or extensor bursts) and in kinematics events (e.g. onsets of flexor or extensor phases). Among the neurographic events occurring in a limb during locomotion, the onsets of the eng (or emg) flexor bursts are events of significance for interlimb coordination because they occur synchronously at a reasonably predictable time in relation to step movement (English 1978; Forssberg et al. 1980a; Halbertsma 1983; Perret 1983). On the other hand, the kinematic events within the step cycle which are relevant for the study of interlimb coordination remain to be identified, although the knee E1 phase and the onset of the forelimb support phase are probably highly significant

events for the coupling of limbs during stepping (Forssberg et al. 1980b; Halbertsma 1983).

The present results suggest that during fictive locomotion the progression from walking to trotting and then to galloping associated with a decrease of the step cycle duration is essentially achieved by a shift of the time of occurrence of the flexor bursts of the non time-locked hindlimb respectively to the three other limbs; the transition between two forms of interlimb coupling being complete within 1 or 2 step cycles. Note, however, that the transition can occur without any change in the fictive step cycle duration (see Fig. 1B). These observations support the view that the switch from one coordination pattern to another results from a transition from one motor program to another for the two hindlimbs (Miller et al. 1975b; Halbertsma et al. 1976). This does not exclude the possibility that during actual locomotion movement-related afferent inputs, which play an important role in the changes of interlimb coordination during stepping (Grillner and Zangger 1979; Kniffki et al. 1980; Wetzel et al. 1976), bring out other strategies used during gait transitions (English and Lennard 1982). On the other hand, since supraspinal structures are involved in interlimb coordination during stepping (Shik et al. 1966), a greater variability in the transition patterns is expected in the intact animal stepping overground because of the continuous adjustment of the gait linked to particular kinds of behavior in the animal.

3. Central mechanisms underlying interlimb coordination

The phase-locking of the fictive step cycles of the two forelimbs and the variability of the phase relationship between fictive step cycles of the two hindlimbs support the view that the two girdles are controlled by two separate neuronal networks ("girdle generators"), one for each girdle (Viala and Vidal 1979; Cabelguen et al. 1981; Zangger 1981). In addition, the differences between the two girdles as to the shaping of the locomotor bursts in flexor nerves suggest differences between the time courses of forelimb and hindlimb central locomotor commands, although a contribution of the intrinsic properties of the motoneurons cannot be excluded.

The observation that there is not a necessary link between the fictive step cycle duration and the type of coordination of two homologous limbs support the hypothesis that each girdle generator may be considered as having two functionally distinct elements: a rhythm generating one and an output generating one (Perret and Cabelguen 1980; Gelfand et al. 1988). A similar proposal has been made for the central mechanisms generating respiration and scratching (Feldman et al. 1988; Gelfand et al. 1988).

Recent studies in stepping cats with hemisection and longitudinally myelotomized lumbar spinal cord (Kato 1988, 1989) tend to support the hypothesis that separate neuronal networks control each limb (Miller and van der Burg 1973; Miller et al. 1975b; Edgerton et al. 1976; Halberstma et al. 1976; Grillner and Zangger 1979; Forssberg et al. 1980b). However, this could be the case

for output generators, since, at present, there is no evidence of complete dissociation between locomotor rhythms of a pair of homologous limbs, and therefore no evidence of four individual rhythm generators but only for one at each girdle. The same type of reasoning applies to the model assuming that intralimb coordination during locomotion results from interactions between a series of unit generators (Grillner 1981; see Perret 1983 and Perret et al. 1988 for further discussion).

In conclusion, central coordination of the all four limbs can be viewed as resulting from the interactions between two girdle generators with several different preferred modes of interaction. However, the two girdle generators may be sometimes uncoupled and run freely (Viala and Vidal 1978; Cabelguen et al. 1981).

Since the neuronal networks that constitute the two girdle generators are unknown, any hypothesis about the types of neuronal interactions which might occur between them is highly speculative (see Grillner 1981; Cohen 1988). However, the independence of the time interval between the onsets of the flexor bursts of one of the two pairs of diagonal limbs with respect to the step cycle duration suggests that the two networks interact preferentially according to diagonal relationships. It is noteworthy that a link between diagonal limbs fits well with postural requirements whereas a link between homolateral limbs does not (Gray 1944; Coulmance et al. 1979). On the other hand, it is likely that the central interactions between the two girdle generators are functionally separated: those between the rhythm generating parts of the two girdle generators and those between their output generating parts (Cabelguen et al. 1981).

The neural pathways transmitting the interactions between diagonal limbs observed during fictive locomotion remain to be identified. However, it is very likely that the activity of the neural pathways involved is phasically modulated during fictive locomotion. Therefore, the involvement of neural pathways such as the dorsal spino-cerebellar tract which transmit information exclusively related to mechanical events at the periphery (Arshavsky et al. 1972a,b) can be excluded, although they probably play an important role in interlimb coordination during actual stepping (English 1980).

On the other hand, experiments in high spinal rabbits showing DOPA-induced fictive locomotion of the four limbs (Viala and Vidal 1978) exclude any important role of the supraspinal structures in the coordination of fictive step cycles and emphasize the role of intersegmental pathways connecting the lumbar and cervical enlargements (see also Miller and van der Meché 1976). On indirect grounds, the involvement of long propriospinal pathways (Miller and van der Burg 1973; Miller et al. 1973; Miller et al. 1975a; Halbertsma et al. 1976; Miller and van der Meché 1976; see however Schomburg et al. 1981) or of some of the C3-C4 propriospinal neurons (Arshavsky et al. 1985) in interlimb coordination has been postulated. However, the ascending tracts which give off collaterals at higher spinal segmental levels and exhibit rhythmic activity during fictive locomotion which reflects that of central spinal mechanisms (e.g. the ventral spino-cerebellar and the spino-reticulo-cerebellar tracts) (Perret et al. 1972;

Perret 1976; Arshavsky et al. 1985; Orsal et al. 1988a) could contribute to some aspects of interlimb coordination (Grillner 1975). The observations that the rhythmic activity of ventral spino-cerebellar cells during fictive locomotion peaks around the junction between E1 and E2 phases of the ipsilateral hindlimb step cycle (Arshavsky et al. 1986; Arshavsky et al. 1988), i.e. during a critical turning point for interlimb coordination (Halbertsma 1983; Forssberg et al. 1980b), support this view.

The present results have been obtained during fictive locomotion, i.e. during constant afferent inputs from the periphery. It is however important to elucidate the role of movement-related afferent inputs in interlimb coordination in freely stepping animals before any well-founded hypothesis on the neuronal network generating locomotor interlimb coordination can be formulated. A systematic analysis of the effects of passive movements of different limbs on the efferent pattern during fictive locomotion might be a fruitful approach.

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