# Surface EMG- and coordination dynamics measurements-assisted cerebellar diagnosis in a patient with cerebellar injury

**G. Schalow**

*Cerebellar diagnostic was performed in a patient who had suffered severe cerebellar injury, using kinesiologic (coordination dynamics) and electrophysiologic (surface EMG (sEMG)) means. Since the right cerebellum had been completely destroyed, significant coordination problems (especially on the right side) were expected to be found in addition to balance problems. As compared to a healthy person, coordination between arms and legs was 80% up to 300% worse. Unexpectedly, no pronounced impairment of coordination of the right arm and right leg was found (with respect to the remaining limbs) as a result of the lost right cerebellum. The values of coordination dynamics measured for the right arm and the right leg for exercising in the forward and backward direction were as good as or even better than those obtained for the left side. However, sEMG disclosed a strong impairment of antagonistic muscle activation (spinocerebellum) between the tibialis anterior and the gastrocnemius muscles on the right side upon exercising the legs only on the special coordination dynamics therapy device (similar to a stationary bicycle). The muscles of the right-sided leg worked worse than those of the left-sided leg. But upon exercising both legs and arms on the special device (more integratively), the antagonistic muscle activation improved in the poor right leg by 36% in the short-term memory but not in the good left leg (symmetry improvement). These kinesiological and electrophysiological measurements show that there was no clear ipsilateral correlation between the cerebellum and the laterality of body functions. For different kinds of supported walking sEMG motor programs worsened with the reduction of the support. Probably the damaged vestibulo-cerebellum could not sufficiently coordinate balance any more with walking. When swinging and jumping on the springboard, sEMG motor programs were best for jumping in anti-phase, where maybe more inhibition is activated. It is concluded that coordination measurements and sEMG are powerful tools to evaluate the outcome of cerebellar injury and to provide a diagnostic tool to quantify improvements in the CNS functioning as a result of the coordination dynamics therapy.*

*Key-words: Cerebellum – Injury – Diagnostic – Coordination dynamics – sEMG – Motor program – Symmetry – Antagonicity – Balance*

## Introduction

A movement and learning therapy, called coordination dynamics therapy, has been shown to be able to improve central nervous system (CNS) functioning after stroke (6), traumatic brain injury (7, 18), hypoxic brain injury (17), spinal cord injury (8, 9), in cerebral palsy (11, 15), and in Parkinson's disease (10, 14). Since between one and up to three years of therapy may be needed, with more than 20 hours movement therapy per week to achieve substantial improvement, including functional and structural repair, the efficiency of the treatment is of high importance.

To enhance the efficiency of the treatment, diagnostic means are needed to tailor the therapy to the type of the CNS injury of the patient and to the CNS changes associated with the CNS repair during ongoing treatment. Since the cerebellum is the coordination centre for movements and their interplay

Institute of Exercise Biology and Physiotherapy, Centre of Behavioural and Health Sciences, University of Tartu, 5 Jakobi Street, Tartu 51014, Estonia.

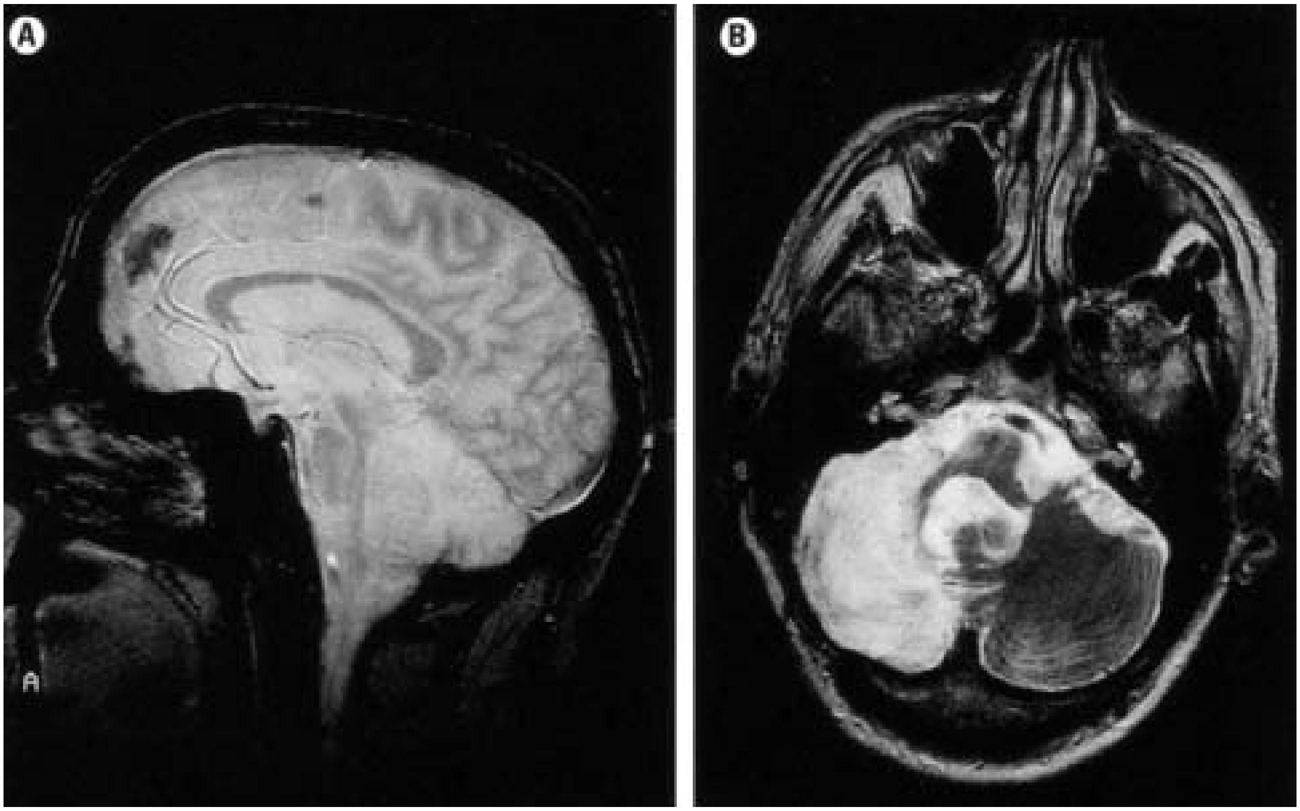


Fig. 1. – Magnetic resonance imaging (MRI). 63-year-old patient who suffered a severe cerebellar and cerebral injury. The cerebellum has been destroyed to approximately 60% (B, light parts of the cerebellum). There is a loss of brain tissue in the frontal lobe (A, dark areas of the forebrain).

with gravity and posture, coordination and symmetry measurements in patients suffering severe cerebellar injury may give us an insight into the CNS regulatory mechanisms and may thus help to make CNS repair more effective.

It will be shown in this paper that surface electromyography (sEMG) and coordination dynamics measurements can be used to diagnose the function of the cerebellum. It will be shown in a patient who suffered severe cerebellar (and brain) injury that symmetry and balance are impaired. In a following paper, forward-backward symmetry will further be analyzed. It will be shown that the anatagonicity impairment between forward and backward moving, quantified in this paper by sEMG, can also be measured in terms of coordination dynamics. The theoretical basis for the Schalow coordination dynamics therapy, including symmetry diagnostic and treatment, will also be given there (21). In another following paper (22), improvements in the CNS functioning will be reported to be achieved in this patient after 6 years of quantified coordination dynamics therapy.

**Method**

Coordination dynamics measurements and surface EMG (sEMG) were used to diagnose cerebellar function. Coordination dynamics of arm and leg movements were measured in terms of arrhythmicity of exercising on the special coordination dynamics therapy device (Fig. 2B). The movements were imposed by the device except the smoothness of exercising. According to the system theory of pattern formation (2), arrythmicity of exercising was the collective or order parameter of CNS organization for these special movements. For further details of the recording of coordination dynamics, see Refs. (15-18, 21, 22).

Differential input was used for sEMG (input resistance = 1MΩ AC coupling). The EMG signals were pre-amplified (1000x, passing frequency 100 Hz – 10kHz) and displayed on a four-beam oscilloscope. Fig. 2A illustrates the sEMG recording layout for walking with sticks.

By function, the cerebellum is divided into 3 parts (1), the vestibulocerebellum (archicerebel-


Fig. 2. – A. Surface EMG recording layout for measuring motor programs during walking with sticks. The author is at the oscilloscope and the wife of the patient is holding the wires to the surface electrodes to reduce movement-induced artefacts. B. Patient with severe cerebellar injury during exercising with both arms and one leg on the special coordination dynamics therapy device in the sitting position. The coordination dynamics (arrhythmicity of exercising) is recorded and displayed on a laptop.

lum), the spinocerebellum (paleocerebellum), and the cerebrocerebellum (neocerebellum). The vestibulocerebellum is the oldest part and it consists of the floccucolnedullar lobe. It is responsible for keeping the balance, i.e. for coordination of the muscle activations for posture and movements against gravity. The spinocerebellum mainly consists of the lower vermis, the paraflocculus, and the intermediary part (paravermal zone). It is mainly responsible for the coordinated action of antagonistic muscles, and communicates strongly with the spinal cord. The cerebrocerebellum (neocerebellum) consists of the lateral part of the cerebellum, and communicates with the cerebrum (the cerebral cortex).

## Results

### *Functional anatomy according to the damage to the cerebellum*

In an accident, a 58-year-old patient suffered cerebral injury and severe cerebellar injury. Low intensity coordination dynamics therapy was administered (22). After 4 years magnetic resonance imaging (MRI) was performed (Fig. 1). Five years later a further MRI was taken to look for macroscopic changes in the brain. The second MRI looked very similar to the first one. No new brain tissue could safely be identified. On the other hand, there was no also atrophy of brain tissue either distinguishable from the last MRI as compared with the image taken 5 years earlier.

Approximately 60% of the patient's cerebellum were destroyed, as can be partly seen from the light parts of the cerebellum in Fig. 1. The right cerebellar hemisphere, the vermis of the cerebellum, and the right middle peduncle of the cerebellum down to the right lateral pons were deficient in substance. The nuclei of the pons may also have been partly damaged. The right cerebellum was nearly completely destroyed (Fig. 1). Aditionally, there was a small substance deficiency in the right frontal paramedian area (of approximately 1 cm in diameter) and a small cortical lesion in the frontal upper gyrus, both due to the injury.

Since the right cerebellum was nearly completely destroyed, strong deficiencies in motor functions on the right side could be expected (according to textbooks (1)), since the efferent fibres of the cerebellar halves are supposed to predominantly influence the ipsilateral body halves. The tractus cerebellorubralis crosses to the other side and the tractus rubrospinalis crosses back. The fibres of the tractus cerebellothalami cross over to the other side and reach the cortex on the other side via the tractus thalamocorticalis. Via the tractus corticospinalis the impulses cross back to the ipsilateral spinal cord.

I will be shown below by comparing the coordination dynamics of the right and left side and of arms and legs and by comparing motor programs of different movements, that the severely injured cerebellum had problems to coordinate balance with movements (which is the task of the vestibulocerebellum) and to coordinate motor control of antagonistic muscles (which is the task of the spinocerebellum). It will further be shown that the recorded symmetries of the motor patterns were not fully in accordance with the assumption of ipsilateral side influence of the cerebellar hemispheres.

### *Kinesiology*

To measure CNS organization with respect to symmetries and coordination by kinesiologic means, the patient exercised on a special device. The arrhythmicity of exercising over time quantified by coordination dynamics was measured for different movements. Symmetry differences between right and left, between arms and legs, and between exercising in the forward and backward direction could be analysed by not involving one arm or leg or arms or legs in the exercise.

### *Coordination dynamics of only arms, only legs, and arms and legs*

To measure movement symmetry differences between arms and legs, the patient exercised with only arms ($\Delta_{arms,forward} = 16.55\ s^{-1}$ and $\Delta_{arms,backward} = 14.8\ s^{-1}$) or only legs in the forward direction ($\Delta_{legs,forward} = 9.2$) and backward direction ($\Delta_{legs,backward} = 23.4$) (Fig. 3). It can be seen from the coordination dynamics values that the patient could exercise better in the forward direction (smaller arrhythmicity of exercising = lower coordination dynamics values) when working with the legs only (Fig. 3A; $\Delta = 9.2$), whereas exercising in the backward direction was better when only using the arms. When exercising with arms and legs, the value of coordination dynamics (arrhythmicity of exercising) was much better (smaller; $\Delta_{forward} = 8.4$, $\Delta_{backward} = 7.0$) as compared with involving legs or arms only. Involving both arms and legs, the patient could exercise better in the backward (Fig. 3H; $\Delta_{backward} = 7.0$) than in the forward direction (Fig. 3G; $\Delta_{forward} = 8.4$). By comparing the values of coordination dynamics values measured for exercising with both arms and legs with those for legs or arms alone, it can be seen that the values for arms and legs individually cannot be derived or extrapolated from the values for involving both arms and legs. With the changing coordination between arms and legs including pace and trot gait and the intermediate coordinations, four-limb movements seem to be completely different from movements performed by arms or legs alone. Exercising with only legs involved is very similar to that on a stationary bicycle.

The corresponding values of coordination dynamics measured for a healthy sporty 28-year-old lady were much better: $\Delta_{arms,forward} = 4.5\ s^{-1}$; $\Delta_{arms,backward} = 5.8\ s^{-1}$; $\Delta_{legs,forward} = 3.5$; $\Delta_{legs,backward} = 5.8$; $\Delta_{forward} = 2.9$; $\Delta_{backward} = 3.9$.

Even though the patient had exercised during at least 6 years on the special device to improve his CNS functioning, his values of the coordination dynamics for arms and legs were worse between 80%

Color??

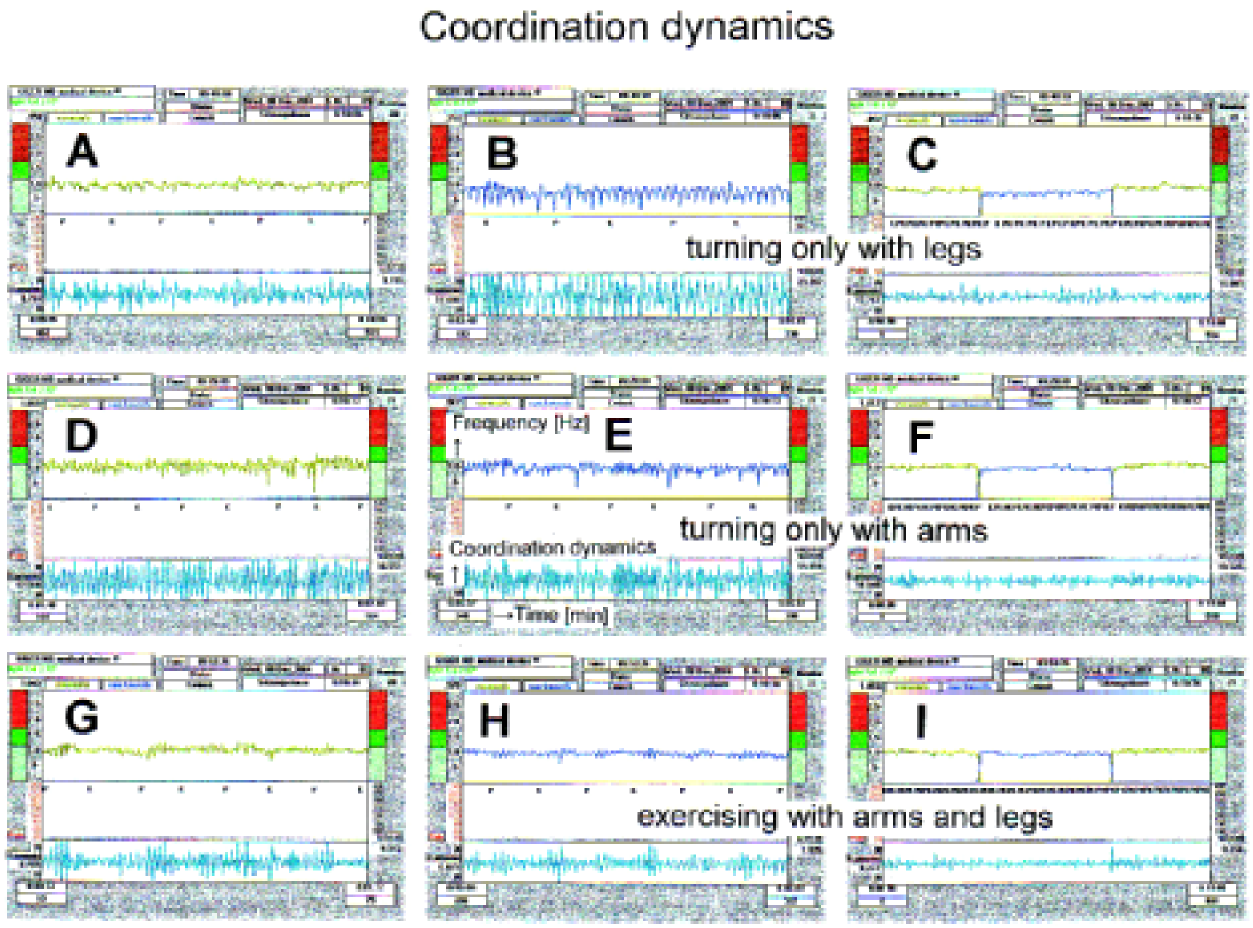


Fig. 3. – Coordination dynamics measurements in a patient with a severe cerebellar injury upon exercising on the special coordination dynamics therapy and measuring device (at the load of 20N) with only legs (A,B,C), with only arms (D,E,F), and with arms and legs (G,H,I). A,D,G = best 1 min record of exercising in the forward direction. B,E,H = best 1 min record of exercising in the backward direction. C,F,I = 10 min sweep showing exercising in the forward, backward, and forward direction. Upper trace = frequency, f; lower trace = coordination dynamics = arrythmicity of exercising. P = pace gait coordination, K = trot gait coordination. „P to K"and „K to P"= coordination changes from pace to trot gait and from trot to pace gait imposed by the device. Note that the legs alone can best do forward movements, the arms alone can best do backward movements, and arms and legs together can best do backward movements as quantified by the value of coordination dynamics. Note further that upon exercising with arms and legs only, there are rhythmic increases and decreases of the coordination dynamics with the changes of coordination (G,H). For forward movements, „K to P"coordinations are mostly better than „P to K"(G), whereas for backward movements, „P to K"´coordinations are better than „K to P"coordinations (H).

and 300% (especially for less integrative movements) than those measured for the healthy person, who only exercised on the device the second time.

*Coordination dynamics for involving the right or the left arm only and both legs or for involving the right or the left leg only and both arms*

To measure side differences in movement coordination between arms or between legs, the patient (right-handed) left out one arm or leg during exercising on the device (Fig. 2B). Since the value of coordination dynamics varies with exercising, the patient started to exercise for 2 min with his arms and legs and subsequently exercised for 2 min with only the right or the left leg (or arm) alternating 3 times, and the mean value was calculated. At the end of the exercise, the patient involved both arms and legs for 2 min as at the beginning of the exercise. Typical best 1 min exercising curves are shown in Fig. 4 with the correcponding coordination dynam-

Color??

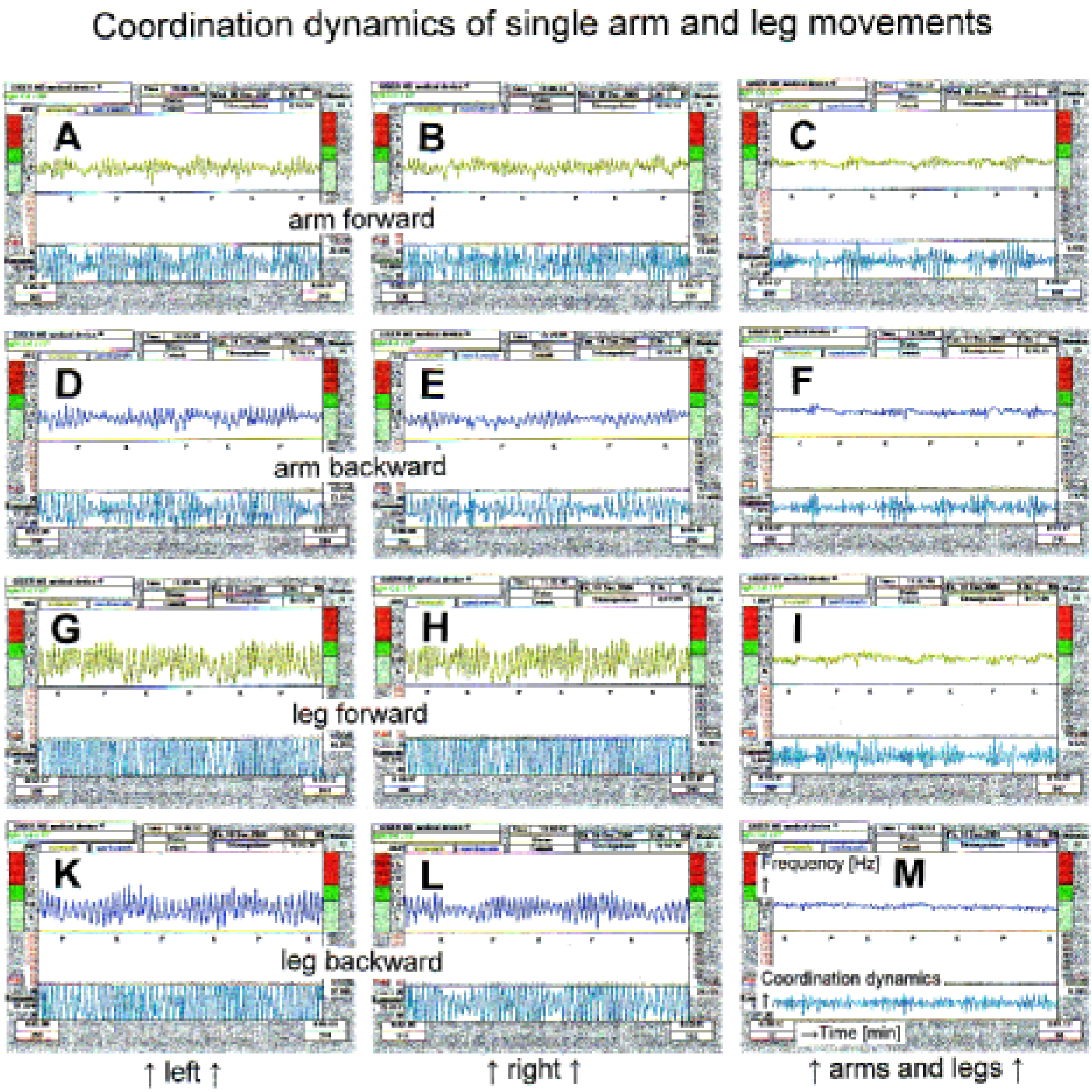


Fig. 4. – Coordination dynamics measurements upon exercising (at a load of 20N) with only the left arm and both legs in the forward (A) and backward direction (D), with only the right arm and both legs in the forward (B) and backward direction (E), and with only the left leg and both arms forwardly (G) and backwardly (K), and only with the right leg and both arms in the forward (H) and backward direction (L). C,F,I,M. Exercising with arms and legs after using only one arm or one leg. P = pace gait coordination, K = trot gait coordination. „P to K“and „K to P“= coordination changes from pace to trot gait and from trot to pace gait imposed by the device. Note that the right arm and leg can do better movements in the forward and backward direction (B,E,H,L) than the left arm and leg (A,D,G,K), as quantified by the coordination dynamics values. Single arms can move more in a coordinated manner (A,B,D,E) than single legs (G,H,K,L), as quantified by the amplitude of arrhythmicity of exercising. Note further that the more easily performed coordinations are different for single arms and legs and for exercising in the forward and backward direction, as can be seen from the (upper) frequency and the (lower) coordination dynamics traces. For example, less arrhythmicity (A) of „K to P“coordinations was observed for the left arm for exercising in the forward than in the backward direction (D).

ics values: $\Delta_{left,arm,forward} = 20.1$; $\Delta_{right,arm,forward} = 19.6$; $\Delta_{left,arm,backward} = 22.0$; $\Delta_{right,arm,backward} = 17.6$; $\Delta_{left,leg,forward} = 44.9$; $\Delta_{right,leg,forward} = 44.8$; $\Delta_{left,leg,backward} = 37.7$; $\Delta_{right,leg,backward} = 29.7$. The values of coordination dynamics (and the curves) suggest that for the exercising in the forward and backward direction the right arm moved slightly better than the left arm. Less favourable values were measured for the legs. For exercising in the forward direction, the right and the left leg moved very similar, as the coordination dynamics values were very similar (44.8 and 44.9). For exercising in the backward direction, the right leg (29.7) was better than the left leg (37.7). For exercising in the forward direction, the right-sided arm and leg were very similar to the left-sided arm and leg. However, for exercising in the backward direction, the right arm and right leg were better than the left ones. The better (or the same) quality of movements on the right side was unexpected, since poorer movement coordination was expected on the right side due to the destroyed right cerebellum with the ipsilateral impairment of function (see functional anatomy, above).

The corresponding coordination dynamics values (means) measured for a right-handed healthy sporty 28-year-old physiotherapist (same as above) were (in the brackets values measured for the patient are given for direct comparison): $\Delta_{left,arm,forward} = 6.57$ (20.1); $\Delta_{right,arm,forward} = 5.88$ (19.6); $\Delta_{left,arm,backward} = 8.57$ (22.0); $\Delta_{right,arm,backward} = 6.93$ (17.6); $\Delta_{left,leg,forward} = 21.5$ (44.9); $\Delta_{right,leg,forward} = 21.5$ (44.8); $\Delta_{left,leg,backward} = 19.9$ (37.7); $\Delta_{right,leg,backward} = 21.5$ (29.7). The volunteer could coordinate her right hand with her legs slightly better than the left hand for exercising in the forward and backward direction. Moreover, for exercising in the forward and backward direction she could coordinate her right and left leg very similarly with the arms.

The volunteer could coordinate arm and leg movements much better (lower values) than the patient (values in the brackets), even though the patient had exercised for more than 6 years on the device and the volunteer had not. The differences in coordination dynamics values between the patient and the volunteer were bigger between the hands than between the feet. This may suggest a more significant impairment of the coordination of the arms and hands as compared with the legs due to the severe cerebellar (and brain) injury.

*Electrophysiology*

After a severe cerebellar injury the phase and frequency coordination between neuron firing will be impaired (5, 13). This will have consequences at different levels of CNS self-organization, including the level of motor programs, which can be measured by surface electromyography (sEMG). Motor programs were therefore recorded from different muscles during exercising on the special coordination dynamics therapy device and during different kinds of walking (with different amount of balance needed), running, and jumping on springboard to identify impairments. It will be attempt to allocate functional impairments to the different parts of the cerebellum.

When the patient exercised on the special device in the sitting position at 100N, only using legs or using arms and legs (similar as in Fig. 2B), he had not to keep balance. Deficits in the motor programs will therefore mainly be induced by the injury of the spinocerebellum (responsible for coordination, especially between antagonistic muscles).

*Symmetry improvement of motor programs of antagonistic muscles by increasing the integrativity of the movement (spinocerebellum)*

The surface electrodes were placed on the right and left tibialis anterior and the right and left lateral gastrocnemius muscles. When the patient only exercised with the legs, the left gastrocnemius muscle became activated too late with respect to the left tibialis anterior muscle (Fig. 5A, at $\varphi = 200°$ instead of 180° (antagonistic muscles)) for exercising in the forward direction, and it became activated to early for exercising in the backward direction (Fig. 5B, at 150° instead of 180°). The antagonicity of the motor programs thus showed pathologic symmetry between exercising in the forward and backward direction, namely $\Delta\varphi_{forward} = 20°$ against $\Delta\varphi_{backward} = -30°$. When exercising with arms and legs (Fig. 5C,D) this asymmetric coordination did not change in the (better) left leg.

However, an improvement of the symmetry of antagonistic coordination between the gastrocnemius and the tibialis anterior muscles could be observed in the right leg when exercising in the forward or backward direction using arms and legs as

Color??

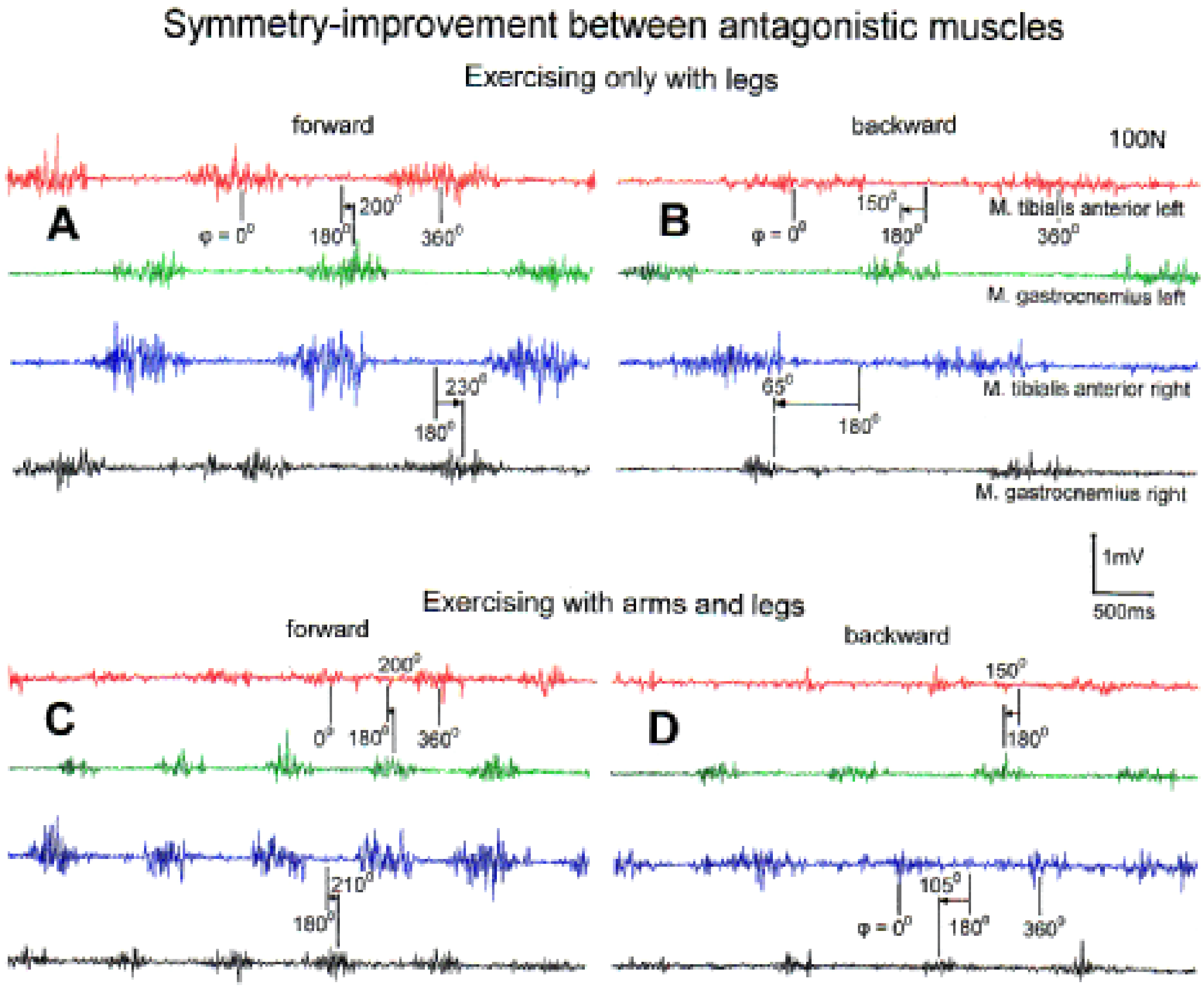


Fig. 5. – Motor programs of right and left tibialis anterior and gastrocnemius muscles recorded by sEMG for the patient with a severe cerebellar injury upon exercising on the special coordination dynamics therapy device in the forward (A,C) and backward direction (B,D) only using legs (A,B) and with arms and legs (C,D). Note that the gastrocnemius muscle is not activated properly antagonisticly with respect to the tibialis anterior (at 180 degree): it gets activated ealier or later, depending on whether movements are performed in the forward or backward direction and upon whether only legs or arms and legs are used.

compared to only using the legs. Upon exercising in the forward direction only using legs, the right gastrocnemius muscle became activated to late with respect to the right tibialis anterior muscle (Fig. 5A, at 230° instead of 180°; $\Delta\varphi_{\text{forward}} = 50°$), and to early for exercising in the backward direction (Fig. 5B, at 65° instead of 180°; $\Delta\varphi_{\text{backward}} = –115°$). When exercising in the forward direction with arms and legs, the right gastrocnemius muscle was not activated that late (Fig. 5C, only at 210° instead of 180°; $\Delta\varphi_{\text{forward}} = 30°$). When exercising in the backward direction, the right gastocnemius muscle did not get activated as early with respect to the right tibialis anterior muscle (only at 105° instead of 180°; $\Delta\varphi_{\text{backward}} = –75°$). Thus, it may be stated that the antagonistic coordination between the right tibialis anterior and the right gastrocnemius muscles improved for exercising in the forward and backward direction by 20° and 40° respectively upon exercising with arms and legs as compared to using only the legs. More generally speaking, this antagonicity symmetry between the tibialis anterior and the right gastrocnemius muscles improved by 60° for exercising in the forward and backward direction upon exercising with both arms and legs. During this more integrative exercising on the special coordination

Color??

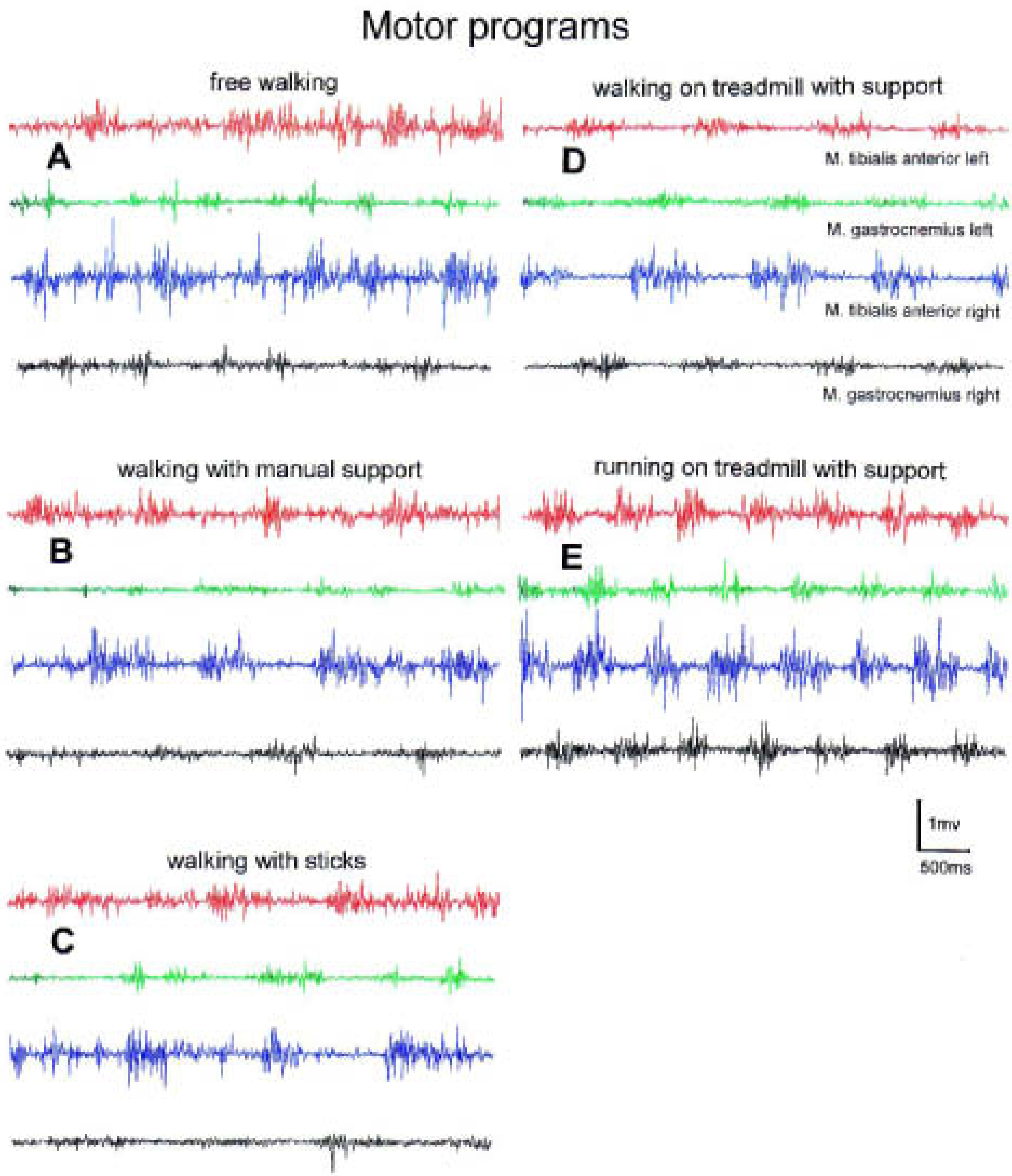


Fig. 6. – Surface EMG motor program of the right and left tibialis anterior and gastrocnemius muscles for free walking (A), walking with manual support (B), walking with sticks (C), walking (D) and running (E) on the treadmill with support. Note that the motor programs for walking with strong support (D,E) are much better than those for walking with little or no support (A,B,C).

dynamics therapy device using both arms and legs, the antagonistic activation of the tibialis anterior and the gastrocnemius muscles improved in the short-term memory. Since it is the spinocerebellum that is supposed to be responsible for the antagonistic muscle coordination, the main improvement in the short-term memory may be located in the spinocerebellum.

*Learning in the short-term memory from the better opposite side*

The better (with respect to antagonistic activation) left side did not improve, whereas the poor right side did improve by 36% ($\Delta\varphi_{forward} - \Delta\varphi_{backward}$ reduced from 165° to 105°). With the integrativity increasing from coordinated leg movements to coordinated arm and leg movements, the better left side remained unchanged, whereas the poor right side improved by 36%. This one-sided symmetry improvement can be interpreted in the way that the poor right side learned in the short-term memory from the good left side. This learning effect may be sited in the spinocerebellum and/or in the spinal cord (co-movement).

*Motor walking programs and balance (Vestibulocerebellum)*

Subsequently, I studied, how did the motor program of walking change when the patient had to keep more balance by himself. Since the vestibulocerebellum was also heavily damaged, increasing motor program deficits for increasing balance needs could have been expected. Fig. 6 shows sEMG motor programs for free walking (Fig. 6A) and for supported walkings (manual support) (Fig. 6B), walking with sticks (Fig. 6C), walking on treadmill (Fig. 6E), and running on treadmill (Fig. 6E). The motor programs for free walking (A) were worse than those for the different kinds of supported walking (B-E). With the increasing support (from B,C to D,E) the motor programs improved. Obviously, the patient had balance problems: upon spending efforts to keep more balance by himself, his motor programs became worse. The interpretation of this worsening of the motor programs with the increasing balance needs is that upon free walking, the damaged vestibulocerebellum could not sufficiently coordinate balance any more with walking.

*Motor programs when swinging and jumping on springboard*

To find out what motor programs are best upon performing rhythmic, dynamic, stereotyped movements (functional repair on the neural ensemble level) on springboard, sEMG was recorded for the different kinds of springboard movements.

Motor programs upon swinging and jumping on springboard are shown in Fig. 7. For swinging (Fig. 7A) the tibialis anterior and gastrocnemius muscles were only little activated rhythmically, i.e. no real motor program could be seen. When jumping in in-phase, the leg muscles were more activated and motor programs could partly be identified (Fig. 7B). In the right tibialis anterior muscle synchronized oscillatory firing of motor units (pathologic) can be seen (see Discussion). For jumping in anti-phase with (Fig. 7C) and without support by a therapist (Fig. 7D) the motor programs were quite good, even though rhythmic firing of motor units can also clearly be identified during the motor bursts (right gastrocnemius in Fig. 7D).

The conclusion for the treatment with respect to exercising on springboard is that jumping will entrain the neuronal networks of the patient better than swinging, since real motor programs could only be identified for jumping.

*Impairment of functions of the cerebrocerebellum*

The patient had problems with precise and goal oriented movements like eating, drinking, using keys, playing piano, and solving dexterity tests. These properties of the cerebellum were not analyzed in this paper.

**Discussion**

*Functional anatomy*

Due to an accident, the right side and partly also the left side of the cerebellum of a 57-year-old patient were completely destroyed (Fig. 1). According to the functional anatomy described in textbooks (1), an impairment of the function and coordination mainly on the right side of the body can be

Color??

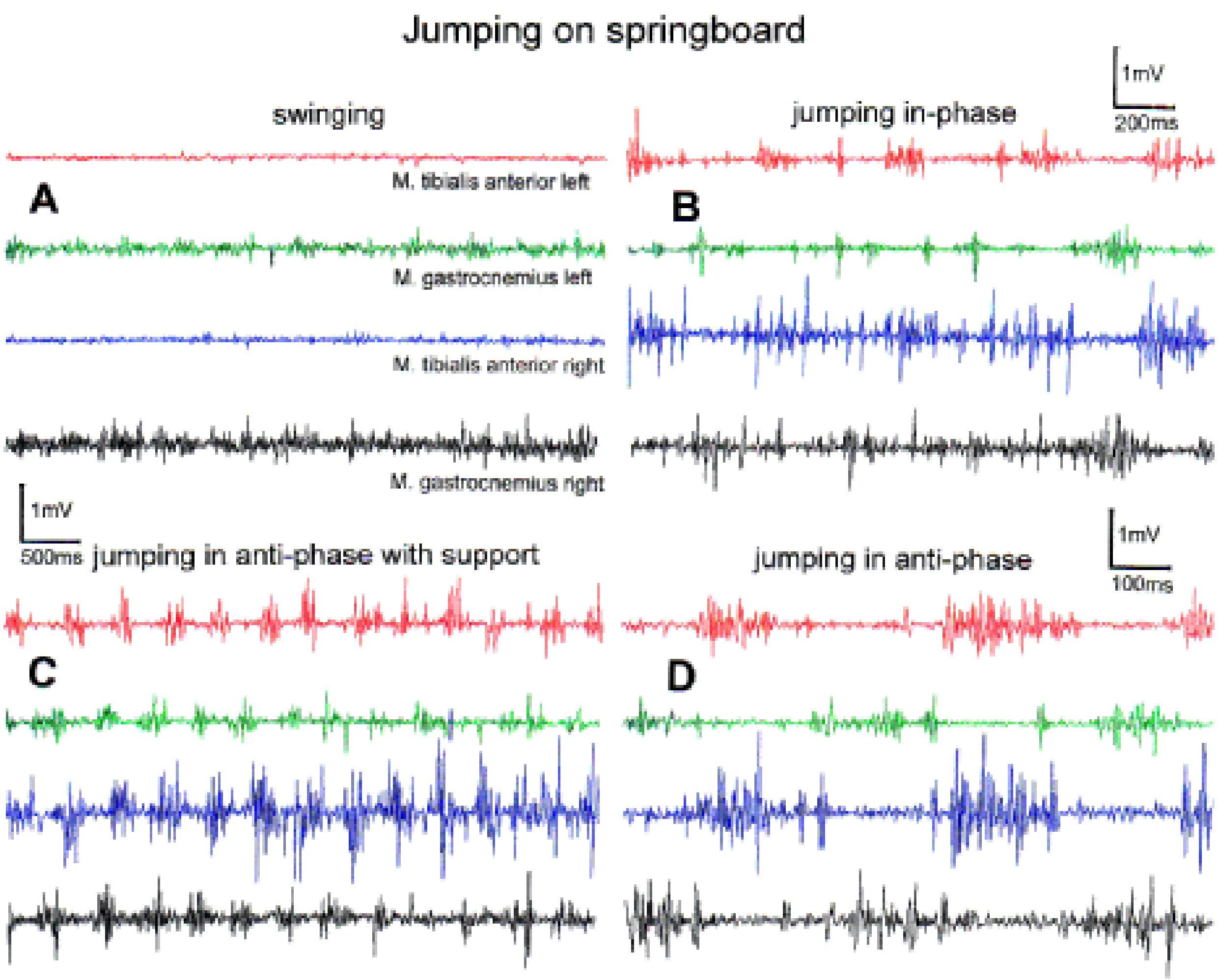


Fig. 7. – Surface EMG motor program of the right and left tibialis anterior and gastrocnemius muscles for swinging (A) and jumping on springboard in-phase (B), in anti-phase with support (C), and in anti-phase without support (D). Note that the motor programs are better for jumping in anti-phase (C,D) than for jumping in in-phase and swinging. Note further that continuous synchronous oscillatory firing of motor units can be seen on the trace taken from the right tibialis muscle for jumping in in-phase (B).

expected. Measuring of the coordination between one arm and the other arm and the legs or between one leg and the other leg and the arms showed that the coordination between the right arm or right leg and the remaining limbs were still better than the coordination between the left-sided arm or leg and the other limbs, even though the right cerebellum was completely destroyed. The coordination dynamics measurements therefore did not show stronger ipsilateral function impairment.

The electrophysiological measurements however showed a partly more significant impairment on the right side. For exercising in the forward and backward direction, there was stronger impairment of the antagonicity (deviation from $\Delta\varphi_{\text{forward,backward}} = 0°$) of the antagonistic leg muscles tibialis anterior and gastrocnemius on the right ($\Delta\varphi_{\text{forward}} = 50°$, $\Delta\varphi_{\text{backward}} = -115°$) than on the left side ($\Delta\varphi_{\text{forward}} = 20°$, $\Delta\varphi_{\text{backward}} = -30°$). Other antagonistic muscle pairs were not measured.

These kinesiological and electrophysiological measurements show that there was no clear ipsilateral correlation between the cerebellum and the laterality of body functions. A very detailed comparison between the cerebellar injury (anatomy) and the functional impairment is very difficult or not possible at all as the CNS damage cannot be evaluated exactly (including nuclei and tract fibres). There may also be further CNS damage, which may not be detected by the MRI.

*Impaired symmetry between exercising in the forward and backward direction*

The special coordination dynamics therapy and recording device offers the possibility of comparing forward and backward movements since forward and backward movements are very similar to each other. Right-left differences can also be easily evaluated by not using one leg or one arm during the exercising (Fig. 2B). Asymmetries in the CNS functioning can therefore be measured on the motor pattern level (by sEMG) and on the movement level (via coordination dynamics).

On the motor pattern level (by sEMG), the antagonicity impairment between the tibialis anterior and gatrocnemius muscles on the right side were bigger for exercising in the backward ($\Delta\varphi_{\text{backward}} = -115°$) than for the forward direction ($\Delta\varphi_{\text{forward}} = 50°$) (Fig. 5).

Forward-backward symmetry impairment could also be recorded with the coordination dynamics when the patient with cerebellar injury exercised at loads between 100 and 200N in the forward and backward direction on the special device. The movement patterns with the highest stability (attractor states) showed a nearly mirror-image shift with respect to the pace and trot gait coordinations for forward and backward exercising (Fig. 1 of (21)).

Many asymmetries were observed on the movement level. When, e.g., using arms and legs the coordination dynamics values were different for the forward ($\Delta_{\text{forward}} = 8.4$) and the backward direction ($\Delta_{\text{backward}} = 7.0$), even though the patient had exercised for several years on the special device equally in the forward and backward direction. Sometimes, the difference between the forward and backward direction was small, it often was large. Upon exercising with only the arms the difference was (in this patient) small ($\Delta_{\text{arms,forward}} = 16.55\ s^{-1}$ and $\Delta_{\text{arms,backward}} = 14.8\ s^{-1}$); large differences were seen upon exercising with the legs only ($\Delta_{\text{legs,forward}} = 9.2$ and $\Delta_{\text{legs,backward}} = 23.4$). When the patient was asked to exercise with arms and legs but without using one leg or one hand (to measure side differences), varying differences between exercising in the forward and backward direction were observed (see above). In this patient many symmetries of the CNS were strongly impaired.

When studying the different coordinations between arm and leg movements in healthy subjects, differences could also be observed (see above). Symmetry impairment in CNS functioning were even observed in athletes: e.g., the values for low-load coordination dynamics were worse for exercising in the backward (6.9) than in the forward direction (6.0) (20). In physiotherapists, even larger differences in low-load coordination dynamics values could be observed between exercising in the forward and backward direction ($\Delta_{\text{forward}} = 5.9$; $\Delta_{\text{backward}} = 9.4\ s^{-2}$) (20).

The difference in the CNS organization between this patient and healthy persons is that healthy persons can improve their coordination dynamics between arm and leg movements with respect to symmetries. For patients with severe CNS injuries, and especially with severe cerebellar injuries however, it seems to be not so easy to improve the symmetries in their CNS organization.

*Implications of symmetry learning for the therapy*

Learning transfer from one hand movement to the symmetric one has been reported to occur (2), which means that the symmetry counterpart improves without being trained itself. It has been shown herein (see above) that the antagonicity between the tibialis anterior and gastrocnemius muscles in the poor right leg improved in the short-term memory by 36% when increasing the integrativity of exercising by changing from only leg movements to coordinated arm and leg movements. Assuming that repeated improvements in CNS functioning in the short-term memory repeatedly will slowly also become reflected in the long-term memory would mean that there is learning transfer with respect to the improvement of antagonicity from the left leg to the right leg.

Improvements of symmetries of movements are used in coordination dynamics therapy. A certain movement can be also improved by training the symmetry counterpart. If for example, the walking pattern on the right side has been impaired in a stroke patient for a few years, this pathologic walking pattern has become an old-learned movement and is difficult to improve. The symmetry counterpart, namely backward walking, has however not become an old-learned movement after injury. Additional training of backward walking will therefore more efficiently improve forward walking by learning transfer.

In conclusion, movements and especially automatisms have to be trained with their symmetry counterparts to enhance the efficiency of CNS repair.

*Symmetry improvement of CNS functioning during development in comparison with those after CNS injury*

Coordination dynamics between arm and leg movements in the forward and backward direction has been shown to substantially improve during CNS development by exercising on the special coordination dynamics therapy device (16). Also, the symmetry between exercising in the forward and backward direction improved (16). Besides coordination dynamics improvement also symmetry improvements may thus be of importance to improve CNS functioning in the injured as well as normally functioning CNS (21). It seems worthwhile to further study improvement in CNS organization with respect to coordination and symmetries during individual development (17, 18) to see what can be learned from the improvements of CNS organization during individual development for CNS repair.

*Giving emphasis upon training movements for which the motor programs are best*

The motor programs of the tibialis anterior and gastrocnemius muscles were shown to be better for jumping than for swinging on springboard (Fig. 7). Since the motor programs were still better for jumping in anti-phase than for jumping in in-phase (Fig. 7), jumping in anti-phase will be more beneficial for improving neuronal network organization than jumping in in-phase and should be trained more often. Also the pathologic synchronized oscillatory firing of motor units (see below) seamed to be reduced in the anti-phase jumping mode. Jumping in anti-phase may activate more inhibition. Consequently, jumping in anti-phase should be predominantly trained in this patient at that repair stage.

*Pathologic synchronized oscillatory firing of motor units.*

Surface EMG (12) and recordings from single human neuron axons (3, 4, 5) showed that motoneurons and motor units fired coordinated oscillatory so as not to synchronize to avoid rhythmic movements of muscles and tremor. Because of impaired inhibition (lateral field and other inhibitions) motor units in patients with Parkinson's disease synchronize strongly and give rise to strong tremor (13). There is indication that in patients with Parkinson's disease oscillatory firing $\alpha_2$-motoneurons (innervating FR-type muscle fibres) synchronize their firing to which $\alpha_1$-motoneurons (innervating FF-type muscles fibres) synchronize (13). Synchronized oscillatory firing of motor units was also observed in patients after spinal cord injury (see Method section of Ref.15). Synchronized oscillatory firing was also observed in the patient with severe cerebellar (and brain) injury reported herein (Fig. 7). Pathologic synchronized oscillatory firing seems to frequently occur in the pathologically organizing CNS. There was a suggested less synchronized oscillatory firing upon jumping on springboard in anti-phase (Fig. 7D) than in in-phase (Fig. 7B). This may be explained by inhibition acting more during anti-phase than during in-phase jumping. Another or additional possibility is that observed in patients with Parkinson's disease. An integrative re-organization mechanism was induced which reduced synchronization of oscillatory firing motoneurons (14). The rhythmic dynamic stereotyped movement of jumping in anti-phase on springboard organized a motor program (which improved in the short-term memory), to which synchronized motor units became coordinated, resulting in reduced synchronization of the motor units.

## References


1. BÄHR, M. and FROTSCHER, M.: Duus' Neurologisch-topische Diagnostik, Anatomie – Funktion – Klinik, pages 249-251, Georg Thieme Verlag, 2003.
2. KELSO, J.A.S.: Dynamic Patterns. The Self-Organization of Brain and Behavior. MIT Press, Cambridge, 1995.
3. SCHALOW, G.: Phase correlated adequate afferent action potentials as a drive of human spinal oscillators. *Electromyogr. Clin. Neurophysiol.* 33: 465-476, 1993.
4. SCHALOW, G.: Action potential patterns of intrafusal $\gamma$ and parasympathetic motoneurons, secondary muscle spindle

afferents and an oscillatory firing $\alpha_2$-motoneuron, and the phase relations among them in humans. *Electromyogr. Clin. Neurophysiol*. 33: 477-503, 1993.

5. Schalow, G., Bersch, U., Michel, D. and Koch, H.G.: Detrusor-sphincteric dyssynergia in humans with spinal cord lesions may be caused by a loss of stable phase relations between and within oscillatory firing neuronal networks of the sacral micturition centre. *J. Auton. Nerv. Syst.* 52: 181-202, 1995.
6. Schalow, G.: Stroke recovery induced by coordination dynamic therapy and quantified by the coordination dynamics recording method. *Electromyogr. Clin. Neurophysiol.* 42: 85-104, 2002.
7. Schalow, G.: Improvement after traumatic brain injury achieved by coordination dynamics therapy. *Electromyogr. Clin. Neurophysiol.* 42: 195-203, 2002.
8. Schalow, G.: Recovery from spinal cord injury achieved by 3 months of coordination dynamics therapy. *Electromyogr. Clin. Neurophysiol.* 42: 367-376, 2002.
9. Schalow, G.: Partial cure of spinal cord injury achieved by 6 to 13 months of coordination dynamics therapy. *Electromyogr. Clin. Neurophysiol.* 43: 281-292, 2003.
10. Schalow, G., Pääsuke, M., Ereline, J. and Gapeyeva, H.: Improvement in Parkinson's disease patients achieved by coordination dynamics therapy. *Electromyogr. Clin. Neurophysiol.* 44: 67-73, 2004.
11. Jaigma, P., Schalow, G. and Pääsuke, M.: The effect of 3-month Schalow coordination dynamics therapy on movement coordination characteristics of the limbs in subjects with cerebral palsy. Acta Kinesiologiae Universitatis Tartuensis 9: 66-78, 2004.
12. Schalow, G.: Phase and frequency coordination between neuron firing as an integrative mechanism of human CNS self-organization. *Electromyogr. Clin. Neurophysiol*., 45: 369-383, 2005.
13. Schalow, G.: Tremor in Parkinson's disease patients can be induced by uncontrolled activation and uninhibited synchronization of $\alpha_2$-motoneuron firing to which $\alpha_1$-motoneuron firing synchronizes. *Electromyogr. Clin. Neurophysiol*., 45: 393-406, 2005.
14. Schalow, G., Pääsuke, M., Jaigma, P.: Integrative re-organization mechanism for reducing tremor in Parkinson's disease patients. *Electromyogr. Clin. Neurophysiol.*, 45: 407-415, 2005.
15. Schalow, G., Jaigma, P.: Cerebral palsy improvement achieved by coordination dynamics therapy. *Electromyogr. Clin. Neurophysiol*., 45: 433-445, 2005.
16. Schalow, G.: Functional development of the CNS in pupils between 7 and 19 years. *Electromyogr. Clin. Neurophysiol.*, in press.
17. Schalow, G.: Hypoxic brain injury improvement induced by coordination dynamics therapy in comparison to CNS development. *Electromyogr. Clin. Neurophysiol.*, in press.
18. Schalow, G. and Jaigma, P.: Improvement in severe traumatic brain injury induced by coordination dynamics therapy in comparison to physiologic CNS development. *Electromyogr. Clin. Neurophysiol.*, in press.
19. Schöner, G., Jiang, W.Y. and Kelso, J.A.S.: A synergetic theory of quadrupedal gaits and gait transitions. *J. theor. Biol*. 142: 359-391, 1990.
20. Schalow, G. and Pääsuke, M.: Low-load coordination dynamics in athletes, physiotherapists, gymnasts, musicians and patients with spinal cord injury, after stroke, traumatic brain lesion and with cerebral palsy. *Electromyogr. Clin. Neurophysiol.* 43: 195-201, 2003.
21. Schalow, G.: Symmetry diagnosis and treatment in coordination dynamics therapy. *Electromyogr. Clin. Neurophysiol.*, submitted
22. Schalow, G.: Cerebellar injury improvement achieved by coordination dynamics therapy. *Electromyogr. Clin. Neurophysiol.*, submitted

*Address reprint requests to*
Giselher Schalow
Dr.med.habil.,Dr.rer.nat.,Dipl.Ing.
Untere Kirchmatte 6
CH-6207 Nottwil
Switzerland

www.cdt.host.sk
g_schalow@hotmail.com