Symmetry diagnosis and treatment in coordination dynamics therapy

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Forward-backward movement symmetry of the human CNS was investigated through pattern change during exercising on a special coordination dynamics therapy and recording device in the forward and backward direction. A mirror-image symmetry shift was found in a patient with cerebellar injury for the attractor patterns (movement patterns with the highest temporal stability) for exercising on the special coordination dynamics therapy device in forward and backward direction, with respect to pace and trot gait coordinations. Symmetry diagnosis and symmetry treatment are of importance in CNS repair because of the learning transfer to the movement symmetry counterpart: training of backward walking improves forward walking. The theoretical and practical basis of Schalow Coordination Dynamics Therapy is given in the Method section including symmetry considerations with respect to CNS self-organization.

Key-words: Cerebellum – Injury – System theory of pattern formation – Symmetry – Diagnosis – Treatment – Learning transfer.

Introduction

An efficient repair of the human central nervous system (CNS) requires the understanding of the functioning of the human CNS under physiologic and pathophysiologic conditions as well as an optimum involvement of the repair mechanisms. One important principle of spatiotemporal pattern formation in the human CNS is phase and frequency coordination between the firings of neurons and neural assemblies. As following an injury, malformation or degeneration, this relative coordination with respect to time and space is impaired. Exercising on the special coordination dynamics therapy devices improves phase and frequency coordination and CNS functioning.

However, symmetry of the pattern dynamics seems to be an attribute that also plays an important role in the structuring of the coordination of rhythmic movements (6). Breaking front-rear symmetry was found to account for the difference between straight and reverse walking (29). Further, there is learning transfer from a movement to its symmetry counterpart (7, page 179). Exercising backward walking and crawling may improve forward walking and crawling. Further, symmetry has consequences in terms of transitions between behavioural states. In the asymmetric case lower level of noise and/or perturbation are required to throw the system out of its present state than is required in the symmetric case (Fig. 1 of 27, 6). In neurotherapy, the stability of the movement patterns can be experienced during walking on treadmill. If a patient with an incomplete spinal cord injury walks on treadmill under weight reduction and leg support given by two physiotherapists, he/she can get better into or stay better in the rhythmic walking pattern, if his injury is more symmetric and if the interpersonal coordination between the two physiotherapists (each supporting one leg) is more symmetric. Symmetry and stability thus structure the state space of a multicomponent system with multiple patterns (including pathologic patterns like spasticity) so that only a limited set of transitions are observed (5). Symmetry diagnostic

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and symmetry training with respect to CNS organization are therefore also important during therapy.

In a previous article it was dealt with cerebellar diagnosis (28), right-left, rostral-caudal, and forward-backward symmetry diagnosis in a patient with cerebellar injury. The forward-backward movement symmetry of the coordination of the firing of agonist and antagonist muscles was quantified by sEMG. In the present paper, forward-backward movement symmetry will be analysed in respect of the coordnation of firing of antagonistic muscle activation in a patient with cerebellar injury during exercising on the special coordination dynamics therapy device, i.e. by coordination dynamics. It will be shown that, for high-load exercising, the patterns with the highest temporal stability (attractor states) shifted away in a mirror-image manner from the physiologic position in the coordination pattern dynamics traces, i.e. away from pace and trot gait patterns.

Method

Theoretical basis of the Schalow Coordination Dynamics Therapy

If we want to understand the functioning and the repair of the human central nervous system (CNS), we have at least to understand CNS functioning at the neural, neural assembly, muscular and movement level. We have to discover or identify the laws or principles of CNS organization at the different levels of organization.

The link between neuronal activities (microscopic events) and behaviour (macroscopic events) consist of collective effects (pattern formation) at the microscopic level that create macroscopic order and disorder. At the neural level, communication takes place by cooperation and competition.

Movement level

Coordination dynamics: By cooperative and competitive interplay the many billions of neurons of the human CNS generate dynamics in self-organization which cannot be explained by the properties of the single neurons and neuron assemblies alone. Therefore, a dynamic system theory of self-organization and pattern formation of the human CNS (1, 3, 7, 30) was derived from the concepts of synergetic. Synergetics is the theory of self-organization and pattern formation in non-equilibrium systems (2, 4). Since the amount of information necessary to describe individual states of neurons is very large, ways must be found to select relevant variables to compress the amount of information. In synergetics, methods have been found to compress system complexity to only one or a few degrees of freedom, the so-called order parameters, whose dynamics (equations of motion) are low-dimensional. This dynamic system theory of pattern formation is applied here also to the injured or malfunctioning CNS (on the macroscopic level) to improve CNS functioning by learning including structural repair.

The organization dynamics of the human CNS, viewed through the window of coordinated movements are termed coordination dynamics. Collective variables or order parameters capture the collective coordinated activity of the neurons of the CNS. The specific equations of motion (the dynamics) of these collective variables generate the time course of organizational states.

The collective variables can be designated by the vector **X** and the coordination pattern dynamics can abstractly be formulated by equations of motion (30):

$$d\mathbf{X}/dt = \mathbf{F}_{intr}(\mathbf{X}) \qquad (1)$$

The functional form of the right-hand side of the equation is called vector field and must be modelled for practical application. The major constraint of such modelling is that stable, reproducible patterns are asymptotically stable solutions (called attractors) of these dynamics. If the constraints do not specify a particular pattern, the coordination dynamics are called intrinsic dynamics ($\mathbf{F}_{intr}$). For a mathematical solution of the intrinsic dynamics ($\mathbf{F}_{intr}$) for the jumping on the springboard in the Haken-Kelso-Bunz model (1, 3), see Ref.27.

A further step on the dynamics of the system theory of coordinated pattern formation is to map the behavioural patterns (observed coordination patterns) onto attractors of the order parameter dynamics. In a complex system like the CNS patterns can be generated by the system seeking cooperative stability. Stability is what defines collective states. The system has the tendency to slip into the collective states to which it is attracted. Commonly attractive states and attractors are pictured as a ball in a potential well or more generally in an attractor layout (see Fig. 3 E,G). When an infant crawls, its arms and legs are strongly attracted to the pace and trot gait patterns (attractor states). Changes in CNS functioning are characterized as continuous stabilization and destabilization, over time, of preferred attractor states.

However, coordination patterns are not only determined by the task or biological function. Patterns adjust continuously to requirements from the environment, memory, intention, and support given by the therapist. All the specific requirements are captured by the concept of behavioural information and are made part of the vector field that attracts toward the required patterns. The coordination pattern dynamics, characterized by equations of motion of collective variables, takes now the following form (30):

$$d\mathbf{X}/dt = \mathbf{F}_{intr}(\mathbf{X}) + \Sigma c_{inf}\mathbf{F}_{inf}(\mathbf{X},t) \qquad (2)$$

where $\mathbf{F}_{intr}$ designates the intrinsic dynamics. The sum is over different types of so-called behavioural information, $\mathbf{F}_{inf}$, as environmental, memorized, or intended behavioural information. Each function $\mathbf{F}_{inf}$ is modelled such that, taken in isolation, it defines a stable solution of the dynamics of the required pattern. The relative strength of the different influences is parameterized by c_{inf}. For a mathematical solution to equation (2) for the special movement 'jumping on the springboard' in the Haken-Kelso-Bunz model (1, 3), see also Ref. 27. The equations of motion of the collective variables (2) have important clinical implications for treatment.

1. Behavioural requirements $\mathbf{F}_{inf}$ (like intention, support, and instruction) affect the whole coordination dynamics, including stability, rather than certain coordination pattern itself only.
2. Intrinsic coordination tendencies captured by the intrinsic dynamics influence systematically the performed pattern because the degree to which intrinsic tendencies conflict or agree with the required patterns determines the variability of the performed coordination pattern.
3. Reduction in stability when intrinsic and informational requirements conflict may lead to loss of stability and abrupt change as behavioural information is changed smoothly.
4. The intrinsic dynamics $\mathbf{F}_{intr}$ include vegetative and higher mental functions, which indicate that via exercising coordinated movements with support and instructions ($\mathbf{F}_{inf}$), urinary bladder function and intelligence can partly be repaired following CNS injury.
5. When in an injured CNS with a certain set of behavioural information ($\Sigma c_{inf}\mathbf{F}_{inf}$) the inner coordination dynamics ($\mathbf{F}_{intr}$) cannot be changed any more during therapy, then this set of behavioural information has to be changed (using different $\mathbf{F}_{inf}$) or balanced differently (using different $\mathbf{c}_{inf}$) to further improve CNS organization dynamics.
6. However, the equations of motion of the coordination dynamics (formula 2) provide no information about the specific behavioural information (F_{inf}) with the use of which the CNS can efficiently be repaired in the given patient.

The novel step in this formulation (formula 2) is that the trained movement patterns do not only improve themselves, but also other not trained functions (like vegetative and higher mental functions) of the CNS may improve (learning transfer). Further, we have a theory-based tool at hand to increase the stability of physiologic network states (for example movements) and to decrease the stability of pathologic neuronal network states (different kinds of spasticity). This means that we have a theoretical tool at hand to understand how we can repair the injured or malfunctioning human CNS on the macroscopic level by learning.

Symmetry: Loss of stability of pattern states cannot explain why certain pattern transitions are observed more often than others, when simultaneously multiple patterns are stable. In addition to stability, symmetries structure the state space (all possible pattern states) of a multicomponent system with multiple patterns, so that a limited set of transitions are observed only. Symmetry of pattern dynamics is a property that plays an important role in structuring the coordination of rhythmic movements (6).

If symmetry is impaired in a patient with a CNS injury, the CNS organization switches more easily from movement state into spastic state or into another movement state. In the asymmetric case of CNS injury, also lower level fluctuation (due to noise or a perturbation) is required to 'kick' the system out of its present state than is required with a symmetric potential well (Fig. 1B of Ref.27). The worst situation of asymmetric severe CNS injury is drifting of the CNS organization. In the literature, this situation is referred to as "phase wandering" or "running" (33). As the asymmetric potential well of the pattern dynamics becomes very shallow, relative phase is predicted to phase wrap, that is, to continually roll down the potential function without assuming any particular value of relative phase. Such drifting of CNS organization was observed in severe brain injury, when exercising on the special coordination dynamics therapy and recording device (23). The arm-leg movement patterns with the highest stability (lowest arrhythmicity) drifted continuously during pattern change with respect to the pace and trot gait coordinations (Fig. 8 D of Ref.23).

Macroscopic assessment of coordination tendencies (pattern stability) and symmetries by deviation and differential stability

It is extremely difficult or not at all possible to calculate the coordination dynamics of even special stereotyped movements (of a healthy or an injured CNS) by a mathematical solution to the equations of motion of the collective variables (formula 2) (even using many approximations). A substantial progress in evaluating the quality of CNS organization was therefore achieved when it became possible to assess the dynamics of CNS organization experimentally. The dynamics of CNS organization is partly reflected in the temporal stability of coordination patterns, which are assessed through a process of pattern change. When a subject exercises on the special coordination dynamics therapy and recording device, the device is imposing all the continuously changing coordinations between arm and leg movements between pace and trot gait. There is only one collective parameter describing the coordination tendencies, which is temporal stability of exercising at an own optimal frequency, e.g. 1 Hz. Within one cycle of movement pattern change, the pattern changes between the symmetric pace gait via asymmetric gaits of intermediate coordination between arms and legs to the symmetric trot gait and back to pace gait coordination again. When, e.g. the hand leavers are turned 18 times, the phase φ between the hand lever and the foot paddle on one side changes continuously from 0° in the pace gait position (in-phase) via 180° in the trot gait position (anti-phase) back to the pace gait pattern at 360°. The measure of the temporal stability when evolving through the different coordination patterns are deviations (e.g. slowing down) of the optimal frequency of exercising and the differential stability of exercising, quantified by the time derivative of the frequency (df/dt; df/dt/f). The mean differential stability over one minute of exercising is referred to as coordination dynamics, and is used to quantify CNS functioning. The obtained coordination dynamics values are function specific to the coordinated movement patterns when exercising on this special coordination dynamics therapy and recording device. Since the quality of CNS functioning can be quantified by a single value, progress in CNS functioning can be evaluated in percentages and can be used to judge improvements in CNS functioning during therapy-induced learning in patients or during development.

Symmetry diagnosis of CNS organization can be performed using the special coordination dynamics therapy and recording device. The underlying symmetries of CNS organization can also be found through the process of pattern change. When exercising in the forward and backward direction, forward-backward movement symmetry can be assessed through measurements of movement pattern stability upon pattern change. Leaving one arm or leg out during the exercising (Fig. 2A of Ref.28) allows evaluation of right-left symmetries (Fig. 4 of Ref.28). Turning the leavers with arms or legs only allows measurements of rostral-caudal symmetry (Fig. 3 of Ref.28).

Repair

The System Theory of Pattern Formation provides us with a tool to understand the functioning of the human CNS with ongoing time. With the behavioural information $\mathbf{F}_{inf}(\mathbf{X},t)$ we can change intrinsic dynamics $\mathbf{F}_{intr}(\mathbf{X})$. However, the equations of motion of the coordination dynamics (formula 2) provides us with no information about the behavioural information ($\mathbf{F}_{inf}$) that can be used to efficiently repair the CNS of the specific patient. In every patient, intrinsic dynamics will be different due to the different nature of the injury, the different history of the CNS, and the different genetics of the CNS.

To find out what behavioural information may change the intrinsic dynamics in the direction of wanted repair we have to understand how the human CNS is functioning physiologically and what has changed in the functioning due to injury, malformation or degeneration on the neuron level, on the neural assembly level, on the integrative level, and on the functional anatomy level. Repair really requires thorough understanding of the functioning of the human CNS. The behavioural information includes movements to be performed, manual supports, touch input, instructions, neuro-feedback, and other information. Surface electromyography (sEMG) helps to identify the movement patterns for which the motor programs of the critical muscles are the best ones (Figs. 6,7 of Ref.28, Fig. 3 of Ref.27). Learning or relearning of movements may be understood as change of coordination dynamics (30). How, then, do we learn on the different levels of CNS self-organization after CNS injury, malformation, or degeneration? Compared to healthy person, the rate of learning may differ by the factor of 50 (17). To achieve repair of the CNS, we have to know how the human CNS generates certain functions and what does change upon an injury.

After CNS injury some CNS functions get lost (or functions become pathologic) and the physiologic self-organization of the neuronal networks becomes impaired. Impairment of the self-organization of neuronal networks means impaired phase and frequency coordination between neuron firings, impaired symmetries of CNS functioning, pathologic self-organization of neuronal assemblies (e.g., spinal oscillators), impaired phase and frequency coordination among neuronal assemblies, pathologic recruitment of assemblies, and other impaired organizations.

To repair the impaired phase and frequency coordination, different special coordination dynamics therapy devices have to be used so as to give the injured CNS the opportunity to re-learn (from the devices) the exact coordination in self-organization. To improve the functioning of premotor spinal oscillators (self-organization and recruitment), the patient has to exercise rhythmic, dynamic, stereotyped movements. To achieve functional repair, automatisms and certain movements have to be exercised, which make intrinsic dynamics more physiologic. Also, inborn automatisms like creeping, crawling, walking, running, breathing, swallowing, continence functions, blood circulation, and others will get genetic support for structural repair. By going to the limits (more than 30 hours therapy per week) for more than probably 6 months also some structural repair may be induced. Also movements have to be exercised, which the patient wants to relearn. Old-learned movements remain (at least partly) as attractor states in the intrinsic dynamics and should also be exercised.

Further ideas on how to repair injured or malfunctioning CNS may be derived from studying the development of the CNS to see how developing CNS improves its self-organization (25). In the system theory of motor development (31), a new behaviour is constructed, which is dependent on the input of all the contributing subsystems. We may learn from the development how the ‘feed-forward system’ is self-correcting en route. In healthy infants, there seem to be substantial coordination deficits in the movements of arms and legs (31). Self-corrections ‘en route’ seem to need substantial corrections of the intrinsic dynamics (changing upon the development).

Stability that characterizes the rhythmic movement forms as a whole does not apply to individual, temporal subdivisions (von Holst (32)). This may mean that the splitting of automatisms into submovements may not always be beneficial for repair.

It may be stated in general in respect of CNS repair that timing of neuron firing has to be improved, along with the stability of physiologic movements, whereas stability of the pathologic organizations has to be reduced.

Neuron and neuron assembly level

When exercising on a special coordination dynamics therapy device or when jumping on the springboard, the very exact coordinations, imposed by the devices seem to, bring about the important changes in the coordination dynamics. This means that highly coordinated movement-induced afferent input to the CNS in combination with the efferent output entrains neuronal networks and helps CNS repair. Neurons of the human CNS have been shown to fire in relative phase and frequency coordination. With the single-nerve fibre action potential recording method it could be demonstrated at the level of single neurons that α and γ-motoneurons and primary and secondary muscle spindle afferents fire in phase and frequency coordination (8,9,11,12) and that this coordination is up to a few milliseconds (13). Using surface electromyography (sEMG) relative phase and frequency coordination could be measured at the level of single motor units (21). Relative coordination means that millions to billions of CNS neurons coordinate the phase and frequency of their firing giving rise to intrinsic coordination dynamics, or, in other words, producing CNS self-organization which evolves over time.

Using the single-nerve fibre action potential recording method this relative coordination between neuron firing was shown to be impaired in patients following spinal cord injury (10). In patients with Parkinson's disease sEMG disclosed that oscillatory firing motor units did synchronize their firing (which is pathologic) to give rise to tremor (22). This means that impairment of the relative coordination of motor unit firing produces pathologic motor programs and in turn pathologic movements.

The idea of attempting to improve impaired relative coordination at the neuron and neuron assembly level led to coordination dynamics therapy which resulted in improvements of CNS functioning after CNS injury (14-16, 18-20, 24, 26, 27) up to a partial cure (18). The macroscopic description of the dynamics of coordinated pattern formation (coordinated pattern formation evolving over time) in the form of equations of motion of collective variables or order parameters on the other hand provided a deeper understanding of the integrative organization of the human CNS and a deeper understanding of the coordinated movements during coordination dynamics therapy.

For the time being it is not possible to mathematically formulate coordination dynamics at the single neuron level, at the neuron assembly level or even at a combined level of description, in which the different levels communicate. Still we can partly extract dynamics of coordinated pattern formation from natural impulse patterns of several neurons. Especially phase and frequency coordination between self-organizing premotor spinal oscillators and their driving secondary muscle spindle afferents can be followed up. It seems possible to relate coordination dynamics of the human movement level to coordination dynamics of the human neuron and neuron assembly level.

Functional anatomy and neurogenesis level

In addition to the understanding of CNS functioning and repair at the neuron, neuron assembly and movement level, we need an insight at the level of functional anatomy. We need to know what parts of the brain primarily contribute to certain functions and what functions are conveyed in what tracts. Following injury CNS diagnosis like magnetic resonance imaging (MRI) is important to correlate anatomical and functional impairments and to enable a better understanding of the injury. Exercised movements can then be better adapted to the specific injury of the patient. If the CNS injury is mainly one-sided then symmetric movements are very important to achieve repair.

With respect to the structural repair of the injured CNS we further need to know what movements can substantially induce neurogenesis and to functionally connect the newly built neurons to the existing networks, and with what intensity these movements should be exercised.

Exercising of movements with their symmetry movement counterpart during therapy

The coordination dynamics therapy includes exercising on the special coordination dynamics therapy and recording device (to improve phase and frequency coordination between neuron firing), training of the automatisms crawling, walking, and running, training of old learned movements like climbing staircases, and speech therapy. With the introduction of symmetry diagnostic, more emphasis is put on the training of a movement in combination with their symmetry counterpart like walking in the forward and backward direction, crawling in the forward and backward direction, crab walking to the right and to the left, and exercising on the special device in the forward and backward direction. The learning transfer from a movement to its symmetry counterpart (7, page 179) is important. If, for example, a stroke patient has not been walking physiologically for 5 years this pathologic forward walking has become an old-learned movement and is difficult to change. Through exercising backward walking however (which is new to the patient) we can improve forward walking by learning transfer to the symmetry counterpart without slipping into the pathologic forward walking pattern.

Natural therapy

Hippocrates' ancient wisdom that "natural forces within us are the true healers of disease" is in accordance with the strategy of coordination dynamics therapy to use natural means (mainly movements) for CNS repair. The question remains, how to find and stimulate the natural strategies, especially to achieve structural repair. After denervating one leg of a rat, the rat often eats up the denervated leg, because the leg has no sensitivity and is hinders the animal's movement. If the rat knew that within some months the leg will be re-innervated and the feeling and the functions will at least partly recover, it would not eat it up. Humans on the other hand have the possibility to find out, understand, and use natural means of regeneration and leave destructive operations and therapies out.

Results

Treatment of symmetry impairment

In a previous publication (Fig. 5 of Ref.28) it was shown by surface electromyography (sEMG) that there was antagonicity impairment of CNS functioning with respect to antagonistic muscle activations of the tibialis anterior and gastrocnemius muscles in a patient with severe cerebellar injury. This antagonicity impairment between antagonistic muscles was opposite for exercising in the forward and backward direction. If it were possible to eliminate this opposite antagonicity impairment of antagonistic muscle activation by certain movements, the patient's motor patterns and performance may improve. It was shown further (Fig. 5 of Ref.28) that increasing integrativity of CNS organization resulted in reduced antagonicity impairment. Upon exercising the legs only on the special coordination dynamics therapy device (like on a stationary fitness bicycle) the antagonicity impairment between the tibialis anterior and gastrocnemius muscles was strong (Fig. 5A,B of Ref.28). Upon exercising with arms and legs, this antagonicity impairment reduced (Fig. 5C,D of Ref.28). In the particular patient the antagonicity impairment could thus be influenced by exercising highly coordinated arms and legs movements on the special device. Other highly coordinated four-limb movements may probably also result in improvements of the antagonicity of muscle activation.

Forward-backward symmetry impairment in cerebellar injury

Probably, antagonicity impairments occur in many pairs of antagonistic muscles, different for exercising in the forward and backward direction (mirror shape, measured by sEMG). Therefore, a more integrative measure is needed to quantify antagonicity impairment. Such an integrative diagnosis for antagonicity impairment may partly be available if the patient exercises on the special coordination dynamics therapy device in the forward and backward direction, and coordination dynamics traces are recorded.

Coordination dynamics traces (Fig. 1) show that, in the patient with cerebellar injury, the lack of symmetry between exercising in the forward and backward direction could be made visible and quantified by measuring coordination dynamics (temporal stability) through pattern change. When exercising at loads between 100 and 200N, the values of exercising frequency and coordination dynamics increased and decreased rhythmically for exercising in both the forward (Fig. 1A) and backward direction (Fig. 1B). For exercising in the forward direction however, the arrhythmicity (the value of coordination dynamics) was small to the right side of the pace (P) and trot gait (K) coordinations (Fig. 1A) whereas upon exercising in the backward direction (Fig. 1B), the arrhythmicity was small to the left side of the pace (P) and trot gait (K) coordinations. Thus, there seems to be a mirror-image shift of the arrhythmicity between

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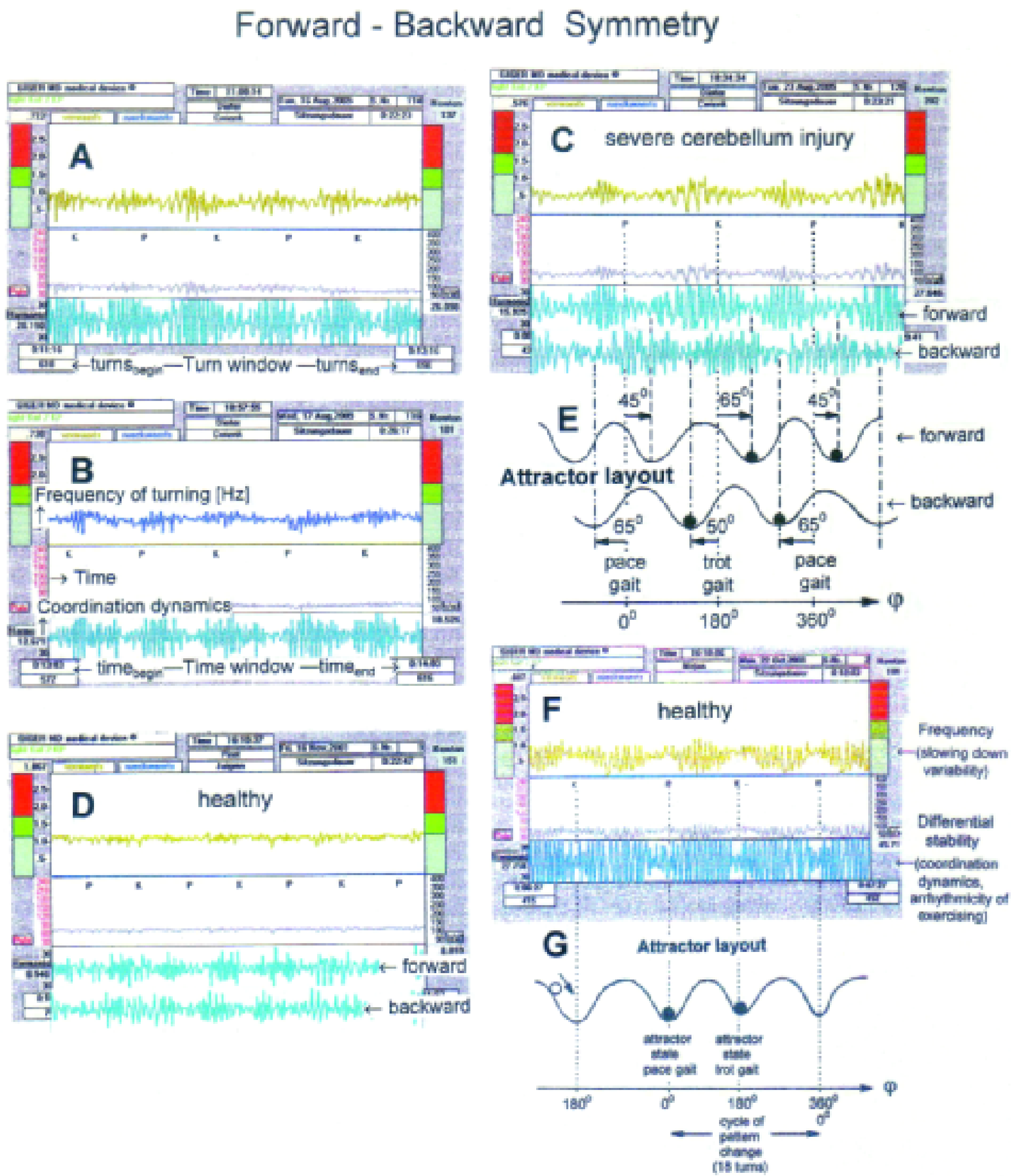

Fig. 1. – Forward-backward movement symmetry impairment in a patient with severe cerebellum injury for exercising on the special coordination dynamics therapy device (A-C). Coordination dynamics figures of a healthy person are shown for comparison (D).

exercising in the forward and backward direction with respect to the pace and trot gait coordinations.

In the healthy person, the smallest arrhythmicity of exercising (the highest pattern stability) was for the pace and trot gait coordinations (Fig. 1F). To make this seemingly mirror image change with respect to exercising in forward and backward direction better visible, the coordination dynamics traces for exercising in forward and backward direction are shown together in Fig. 1C (bottom panel). The recordings were taken one week later to show that patterns of highest stability remained at the same place with respect to the pace and trot gait coordinations, to provide evidence that there was no phase drifting (see Method). It can clearly be seen in Fig. 1C that the periods of smallest arrhythmicity shifted rather symmetrically away from the pace (P) and trot gait (K) coordination position with respect to exercising in the forward and backward direction. When picturing this rather opposite symmetric shift of arrhythmicity of exercising in an attractor layout of pattern formation in the framework of the system theory of pattern formation (5), the attractor states (patterns with the highest stability) shifted away from the pace and trot gait coordination patterns (Fig. 1E). In the attractor layout of a healthy sporty girl (Fig. 1G), drawn from the coordination dynamics recording presented in Fig. 1F, the stable movement patterns (when exercising on the special device) are at the pace and trot gait coordinations. For the patient with the cerebellar injury, the stable movement patterns (small arrhythmicity of exercising) shifted with respect to the cycle of pattern change (bottom part of Fig. 1G) between $\varphi = 45°$ and $65°$ forwardly for exercising in the forward direction, and between $\varphi = 50°$ and $65°$ backwardly for exercising in the backward direction (Fig. 1E). This rather opposite shift of the attractor states shows similarity to the rather mirror picture change of antagonicity impairment of the antagonistic muscle activation of the tibialis anterior and gastrocnemius muscles, measured by surface EMG (Fig. 5 of Ref.28, previous paper). It seems therefore that the special coordination dynamics therapy device can be used to measure symmetry impairments of CNS organization with respect to exercising in the forward and backward direction. The symmetry diagnosis performed using the special coordination therapy and recording device, presented in a preceding paper concerned comparisons between right and left and rostral and caudal. Here, the symmetry diagnosis compared exercising in the forward and backward direction. It remains to be further clarified whether this diagnosis of symmetry coordination dynamics with respect to exercising in the forward and backward direction (kinesiologic measure) actually measures integratively symmetry impairment of several antagonistic muscle pairs (motor programs measured by sEMG, electrophysiologic measure).

Forward-backward movement symmetry impairment in healthy subjects

In healthy subjects the symmetries in CNS organization may also not be ideal. A forward-backward movement asymmetry seems to exist.

For exercising in the forward direction, the value of coordination dynamics obtained for the physiotherapist ($\Delta = 8.0\,s^{-2}$, trained) was much smaller (better) (Fig. 1D) than that for the patient ($27.6\,s^{-2}$, strongly trained) (Fig. 1D). For exercising in the backward direction, the coordination dynamics trace of the physiotherapist is quite good with respect to symmetry (Fig. 1D). The stronger arrhythmicity (high pattern instability) mostly occurs for the difficult intermediate coordinations between the pace and trot gait coordinations. For exercising in the forward direction (Fig. 1D), the stronger arrhythmicity is slightly shifted away from the middle position between the pace and trot gait coordinations. Thus, the symmetry with respect to movements in the forward and backward direction is probably suboptimal even in healthy sporty persons. Also, athletes differed in their coordination dynamics values for low-load exercising in the forward and backward direction (28).

Discussion

Symmetry improvement

It could be shown in a previous and in this paper that in the patient with cerebellar injury the symmetries in the arm-leg pattern dynamics were strongly impaired. Symmetry of the pattern dynamics is a property that plays an important role in the structuring of the coordination of rhythmic movements (6). Front-rear symmetry was found to account for differences between straight and reverse walking (29). Not only could mirror-picture symmetry impairments of antagonistic muscle activation for exercising in the forward and backward direction be seen on the movement level (Fig. 1) but also on the motor pattern level (Fig. 5 of Ref.28, previous paper). Since after spinal cord injury there is impairment of also the premotor spinal oscillators for activation for the motor programs, also neural assemblies are impaired (10) in their self-organization with respect to symmetry as are their driving muscle spindle afferents. Premotor spinal oscillators have two driving phases from secondary muscle spindle afferents per oscillation period (180° apart (11)). The in-phase and anti-phase symmetry seems thus to go down to the very single-neuron level as do its impairments and repair.

It is not only phase and frequency coordination between neuron firings that has to be improved in the self-organization of the human CNS, but also the coordination between neuron firing has to be improved with respect to the symmetries in CNS organization.

More coordination dynamics symmetry data are needed from healthy persons for comparison. In patients with CNS injury, training methods or programs have to be developed to reduce the lack of symmetry especially with respect to movements in the forward and backward direction and, hopefully, to also improve the antagonicity of antagonistic muscles. Symmetry improvements of CNS organization with respect to exercising in the forward and backward direction with ongoing therapy may also have to be quantified.

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