University of Groningen

Assessment of motor recovery and decline

Mulder, T.; Zijlstra, W.

[Link to publication in University of Groningen/UMCG research database](#)

Review

Assessment of motor recovery and decline

Theo Mulder [a],*, Wiebren Zijlstra [a], Alexander Geurts [b]

[a] *Institute of Human Movement Sciences, University of Groningen, P.O. Box 196, 9700 AD Groningen, The Netherlands*
[b] *Sint Maartenskliniek-Research, P.O. Box 9011, 6500 GM Nijmegen, The Netherlands*

Abstract

Assessment of motor disorders forms an important ingredient of neurology, rehabilitation medicine and orthopaedics. Until now, however, many of the employed assessment tools are derived from empirical knowledge. Almost no relation exists with modern theoretical notions about motor control. In the present article, motor control theory is reviewed in the light of its potential contribution to understanding motor recovery. An attempt is made to present a theoretical framework for the assessment of motor disorders related to recent insights in motor control. The framework emphasizes the dynamical character of recovery. The principle of output optimization is discussed and it is stressed that compensation plays a permanent role in adapting to damage of the body or to changes in the environment. An assessment procedure is introduced to measure the (mental) costs of this compensation. It is argued that changes in the costs of compensation across time reflect recovery. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Assessment; Recovery; Motor disorders

1. Introduction

After nervous system damage, or damage to the musculoskeletal system, functional recovery usually occurs to some extent. However, inter-individual variability is high and until now relatively little is known about the determinants of recovery. It is of great clinical importance to follow the course of recovery and, when possible, to predict recovery. Measurement and prediction of recovery, in fact, form one of the main challenges facing clinicians today. However, these measurements often are based primarily on empirical knowledge. Furthermore, the majority of the employed clinical assessment procedures is oriented at the disease- or organ level. Only few procedures focus at the functional or behavioral level (see Ref. [1]). This lack of behavior-oriented assessment procedures forms a serious problem for the development and evaluation of

treatment programs. Indeed, impairment-oriented assessment scores may have little relevance for the prediction of daily life functioning.

In the present article a theoretical framework is presented which may function as an impetus for the development of novel behavior-oriented assessment procedures for the treatment and evaluation of patients with motor dysfunction. The framework is based upon modern insights in human motor control. The concepts, *adaptation*, *compensation* and *output-optimization* play a core role in the framework. The article will start by discussing aspects of human motor control which are essential to the proposed framework. Thereafter, the role of adaptation, compensation and the principle of output-optimization in motor recovery are discussed. This discussion will underscore the point that recovery is not a passive process but the result of an organism reacting actively to changes in the environment or to changes in its structural integrity. A framework for studying motor disorders will be proposed that gives rise to new assessment procedures that do take into account the dynamical character of recovery. Experi-

* Corresponding author. Tel.: + 31-50-363-2719; fax: + 31-50-363-3150.

E-mail address: t.mulder@ppsw.rug.nl (T. Mulder).

mental evidence for the merits of such assessment procedures will be presented.

2. Essentials of human motor control

Movement is the output of a hybrid functional system, intimately linked to its environment and designed to solve problems. The adaptability of the motor system of humans and other animals is remarkable and the enormity of the control-problem is underscored by the rather limited success that engineers had in developing robots that can interact successfully with a complex and changing environment. Even the most sophisticated robots are clumsy and inefficient compared to the motor performances of animals. How then is motor control achieved in such biological machines? To answer this question, the continuous availability of information coming from the body (internal) or the environment (external) needs to be stressed. Information is an absolute prerequisite for the adequate functioning of the problem-solving system. Without information the system is not able to function normally, it is more or less 'functionally paralyzed' [2]. Information plays a core role in the selection of the most optimal motor pattern. Since hundreds, sometimes thousands of movement possibilities exist, this selection problem is not trivial. What are the variables that determine the selection?

Although it is impossible to answer this question unambiguously, it is important to consider movement as the (observable) end-result of a continuous interaction between sensory (perceptual), cognitive, and motor processes [3]. The relative contribution of these processes in the selection-process, however, may change according to the complexity or novelty of the task, the skillfulness of the performer, and the integrity of the system [4–7]. Hence, the production of a movement pattern is not the outcome of a strictly hierarchical or top-down organized system but the result of a hierarchical multilevel system with 'higher levels' controlling the invariant global aspects of the action, related to the goal of the movement, whereas the details are being specified more or less autonomously by subordinate structures, sometimes located at the level of the spinal cord.

The role of 'high level' processes becomes dramatically visible in patients with damage to the frontal lobes. These patients are perfectly able to move but are not able to define goals and/or plan their actions. It was Lashley [8] who addressed this problem of serial order and argued that all complex skills from the songs of birds to the trotting horse, the carpenter and the housewife are characterized by serial order. He regarded the serial order problem as central to the understanding of the ability of humans and other animals to learn new sequences of behavior. The essence of such sequences is

that a relatively small number of units or elements need to be re-arranged, re-ordered or reorganized [9]. It can be argued that on basis of 'frontal' or high-level mechanisms functional groupings of muscles can be activated that are ordered in time and constrained to act as co-ordinative structures [10] or muscle synergies [11]. These co-ordinative structures, however, are not fixed coalitions but task- and context-dependent functional couplings so that a large goal-oriented flexibility is guaranteed. After higher centres have initiated the behavioral sequence they need not play a role in any necessary small-scale adjustments and may even remain ignorant of them. As Jordan and Rosenbaum [12] argued, higher levels initiate a dynamical organization in a certain task-space.

Such an architecture indicates that the computational part of the nervous system is not at all comparable to a computer, sequentially processing all kinds of information in some hierarchical order. There is no task-specific wiring pattern for the brain. What characterizes the brain is a set of dynamic regulatory processes under the control of information (input). Modern insights in neuro-anatomy confirm the existence of such variability and indicate that precise point-to-point wiring cannot be the basis for neural maps since large variations across time exist. Brains are not made up of individual cells that accomplish predetermined tasks, nor are they made up of fixed networks of cells that function like coherent organs or rigid oscillators with a specific function. On the contrary, neural cells are of a variety of different types, and the functional 'organs' of the brain are collectivities of self-organizing rule-building groups of cells, whereby the same cells can participate in various networks [13]. When arguing that the brain has no task-specific wiring we do not mean that there are no modality specific cortices but we want to stress the fact that connections within neural networks are not rigid but modifiable by input. Hence, movement is not the result of a fixed sequence of signals transmitted over efferent pathways determining all the muscle-specific details but the end-result of a flexible 'negotiation' between available input and required output, whereby many strategies may lead to the same output. The selection of a certain strategy depends on the complexity and novelty of the task, the skillfulness of the performer, the integrity of the system, the requirements of the environment and on cognitive variables such as motivation, attention and emotion. Shifting between strategies forms an important characteristic of normal healthy motor control. This is the result of an emergent characteristic of the central nervous system, namely the ability to perform cost-benefit analyses leading to the most efficient strategy to reach a goal under the given circumstances.

Movements, even identical movements, are never performed in exactly the same way. Small adaptive

changes occur continuously in order to tune the movement to the actual circumstances. For example, we can produce speech with our mouth full or with a cigar in it. The speech production system adjusts almost immediately to these changes. We can reach for an object, even when wearing a ten-pound iron bracelet. We can move even when the limbs are partially encumbered or restricted. Kosslyn and Koenig [14], from whom this example is borrowed, distinguished between three mechanisms that enable us to accomplish these adaptive adjustments: first, there are low-level corrective mechanisms, partly situated in the spinal cord involving no higher brain activity at all. Secondly, there are cortical mechanisms driven by the movement end-result. Thirdly, the movement instructions can be adjusted so that compensations for an expected perturbation can be made in advance of the start of the movement.

In accordance with the remarks of Kosslyn and Koenig we suggest that a further distinction can be made, namely that between a fast and slow mode of control. A *fast mode of control* refers to the performance of over-learned movements. The control is largely non-cognitive and 'direct', that is to say, the performance takes place without noticeable conscious involvement because information from the periphery activates, almost without any high-level mediation, the most adequate co-ordinative structures. A *slow mode of control*, on the other hand, refers to the performance of movements in the early phases of a learning process or to the performance of very complex movements. Furthermore a slow mode of control often can be observed in patients with damage to the motor system. In these patients the control is largely cognitive and 'non-direct', which means that the execution of movement takes place with substantial conscious involvement and is (often) dependent on visual information.

The main point so far is that the organism is never rigidly fixed in a single mode but has the ability to shift continuously between the available modes of control. Each task situation, combined with the state of the organism, leads to its own optimal strategy. These shifts enable the organism to reach the required goals even under non-optimal conditions. It will be clear that these remarks have relevance for assessment since they indicate that solely analyzing the output characteristics of motor behavior in terms of kinematic, biomechanical and/or electrophysiological aspects of the movement, indeed, reveals information about the characteristics of the final end-result, but the strategic processes leading to this end-result remain hidden. Insight into these processes, however, is of crucial importance for understanding the level of functional recovery of the patient. Assessment procedures, therefore, should be designed in such a way that changes in the adaptive or compensatory strategies across time can be followed. In the next sections, concepts will be discussed which may form an impetus for the development of such assessment procedures.

3. Adaptation

Adaptation refers to the highly individual, subjective and context-dependent nature of the categorizations that every organism must make in order to impose its own unique order on the ever-changing kaleidoscope of signals reaching it through the senses [15]. Formulated in more simple terms, adaptation is the process by which living organisms change in time [16]. This process takes place over different time scales; it may reflect the slowly progressing changes as a result of aging, [17] as well as the fast and almost immediate adaptations observed in stumble-preventing reactions [18], or inter-limb coordination [19–21] during walking. Adaptability forms a crucial characteristic of all animals, even of the lowest ones, and in human beings this ability is extremely large. This adaptive power plays a crucial role in the functional reorganization of the motor system after damage. Hence, learning more about the dynamics of (individual) adaptability is very relevant for understanding the recovery, or decline, of motor function in patients with neurological, orthopaedic and rheumatic motor dysfunctions. Adaptation can be defined in functional (behavioral) or structural (anatomical) terms, or in terms of processes (physiology). In the present paper an in-between position is embraced in which, in accordance with the remarks made above, adaptation is described as *the capacity of the central nervous system to modify its own structural organization and functioning as a result of internal or external (environmental) changes* (see also Ref. [22]).

3.1. Essentials of adaptability

Normally the input-output relations are, to a large degree redundant, that is, central neural networks 'know' the characteristics of the input they receive from the periphery. After damage (e.g. injury, fracture, amputation) these relationships, however, are altered, and the system is forced to change. As early as 1923 Lashley [23] suggested that the organization of the human cerebral cortex could be flexible. But it was in the 1970's that for the first time such a reorganization was demonstrated [24]. During the last decades ample neurophysiological evidence appeared which underscores this neuroplasticity principle. For example, Merzenich and Kaas [25] showed that the adult mammalian somatosensory system is capable of significant functional reorganization after peripheral nerve or spinal cord injury. They showed that the effectiveness of previously existing synapses can be dramatically modified and that

new synapses can be formed. Many other studies showed that cortical sensorimotor representations can be reorganized after peripheral damage [26], after amputation [27–29], after spinal cord injury [30–32], after transient deafferentiation [33], after ischaemic nerve block [34], after stroke [35] and even after arthritis-like inflammation [36]. Spear [37] showed that neurons in the lateral supra-sylvian gyrus that normally are unresponsive to specific visual input can become responsive to these stimuli in the event that normal visual cortical areas are impaired. Cohen et al. [38] showed the existence of cross-modal plasticity in the blind. Area's activated in sighted subjects during the performance of visual tasks became activated in blind subjects in association with tactile or auditory discrimination tasks. However, they indicated also that the susceptible period for this form of functionally relevant cross-modal plasticity does not extend beyond the age of 14 years. Calford and Tweedale [39] mentioned that this adaptive plasticity even showed inter-hemispheric transfer. They indicated that in flying foxes (*Pteropus Scapulatus*) the receptive fields of neuron assemblies, which originally represented the thumb that had been anaesthetized, expanded within a few minutes after the injection. The receptive fields in the opposite hemisphere located on or around the unaffected thumb, however, also expanded.

The above mentioned results clearly indicate the self-organizing character of the central nervous system, that is, the organizational patterns observed in the cerebral cortex are not static but change under external (environmental) pressure or as a result of internal changes. Even the somatotopic representation of the body in the brain is not a fixed entity but the result of an ongoing process in which cortical maps change as the result of a permanent competition between input sources for cortical (processing) space [40]. Hence, stability in maps is the consequence of balanced competition. Changing the balance results in a sequence of changes which in the beginning may seem rather chaotic but finally leads to a new stability. These changes are activity-dependent or 'input-driven' which means that reorganization takes place as a result of input modulation. This implicates that changes may take place not only as a result of removing or decreasing the input but also as a result of increasing the input. Evidence for the latter statement exists as the work of Pascual-Leone and Torres [41] suggested that learning Braille is associated with expansion of the sensorimotor cortical representation of the reading finger. Also Jenkins, Merzenich et al. [42] showed that specific finger exploratory training in monkeys produced a fast and marked increase in the cortical sensory representation of the fingers used for haptic exploration. These findings are important, since they may form the structural basis of therapy in rehabilitation.

A remarkable and dramatic example of such adaptive plasticity can be found in the tactile vision substitution (TVS) experiments performed by Bach-y-Rita [43]. In these TVS-experiments 'visual' information was delivered to the brain via the skin. The output of a small camera (controlled by a blind subject) was displayed on an area of skin, after transduction to a form of energy (delivered by vibrotactors), that was able to activate the skin sensory receptors. These studies of Bach-y-Rita showed that blind persons not only developed the ability to perceive visual information but also learned to use visual means of analysis (parallax and looming) and to subjectively locate the visual information correctly in three-dimensional space, which is quite remarkable.

4. Recovery and decline: the principle of output optimization

Recovery can be seen as forced change; that is, the system is forced to change in order to cope with the violation of its structural integrity. It is important to note that this process of (forced) change is relatively independent of the type of lesion. Indeed, each type of damage will lead to a systemic dysregulation. A peripheral lesion (nerve injury, arthritis, amputation, etc.), therefore, never is solely a peripheral problem but always reflects also a problem in the interaction between the periphery and the brain. The above cited neurophysiological studies clearly support this notion.

The motor system is flexible, that is to say, there is a sustained effort to keep the output optimal even after damage. But how is this possible? How is the sensorimotor system, for example, able to generate relatively unimpaired motor output in spite of the fact that the system may be damaged? The answer is: by using strategic shifts. For example, some loss of proprioceptive input can be tolerated, but when the loss of proprioceptive input exceeds a certain level the system is forced to shift to another control strategy (e.g. visual control or conscious control of movement). This enables the system to keep the output constant or optimal and to reach goals even under pathological conditions. This capacity is termed here *the output optimization* principle. However, although goals still can be reached, they can no longer be reached by exploiting the fast mode of control, as described earlier in the text. Goals are reached now by exploiting the slow mode of control. In spite of the fact that these adaptive shifts have an important survival value, as they permit the system to remain active and to generate motor activities also under pathological conditions, they never are as efficient as the pre-morbid strategies. Hence, the system has to pay a price for its compensatory capacities. It is argued here that this price can be measured and expressed in terms of *costs of compensation*, whereby the

costs of compensation are defined as the level of effort which is needed to keep the output constant or optimal after damage. In this article, we focus on the mental costs of compensation, however, it must be emphasized that metabolic and mechanical changes such as observed after damage of the neuro-muskulo-skeletal system (for example see Ref. [44]), can also be regarded as indicators of the level of effort required for output optimization.

Under normal conditions, when performing activities such as standing, walking, reaching, eating, etc., these costs are negligible since these activities are highly automated. We are able to talk while walking or to walk with eyes closed. However, as soon as automaticity is lost the compensatory costs are increasing. It is important to understand that every type of damage which violates the integrity of the system and creates novel constraints, unknown to the central nervous system, in principle will lead to the (temporary) breakdown of automaticity. This is an important argument because it implies that loss of skillfulness and automaticity is not only caused by central impairments, but in fact by all impairments that may lead to the distortion of the known afferent-efferent equilibrium.

Before discussing what type of tasks are required for measuring the above mentioned costs of compensation it is important to focus in more detail on some relevant aspects of the recovery or re-organisation process (see Fig. 1).

The figure shows two graphs, the upper graph reflects a situation in which the motor system is improving after damage across time. In this case the costs of compensation are decreasing, whereas in the lower graph a situation is pictured in which the motor system is deteriorating across time, leading to a continuous increase in the costs of compensation. The latter situation will finally end with the breakdown of the system, observable at all levels of performance and no longer hidden behind the compensatory strategies. Please note, however, that in both graphs the directly observable output may remain more or less constant across time.

Conventional assessment-procedures are implicitly (or even explicitly) based on the assumption that a linear relationship exists between the observable out-
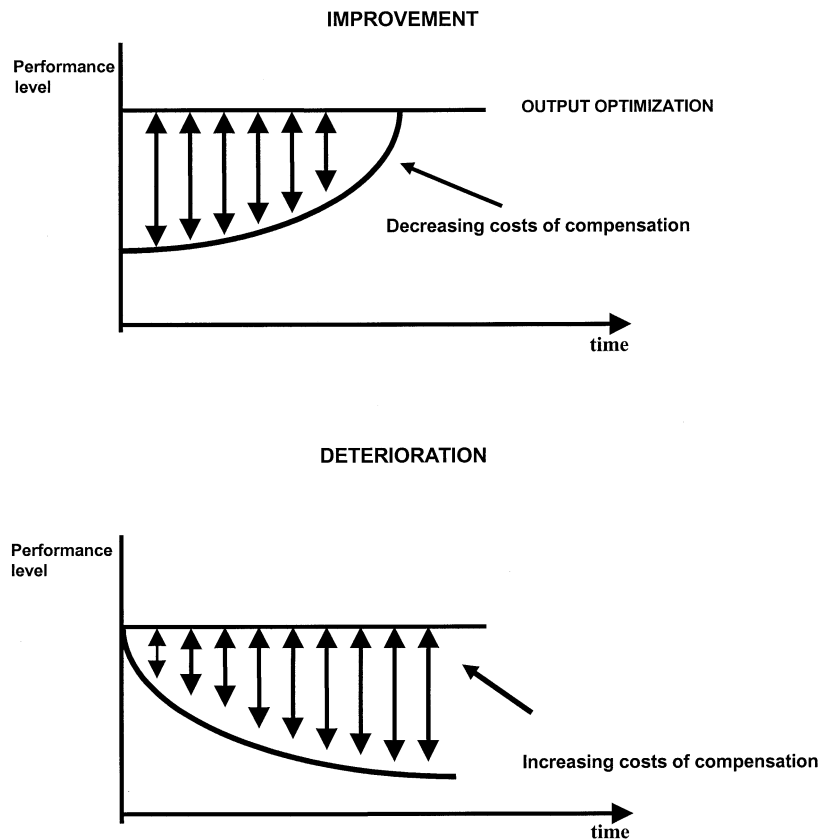
Fig. 1. The upper graph shows the decreasing costs of compensation in an improving neuromotor system. Although the visible output does not change, the amount of effort which has to be invested in the end-result progressively decreases. The lower graph shows a deteriorating neuromotor system. Although the observable end-result still can be reached, the costs become continuously higher across time. Note, however, that in both cases the output remains more or less the same indicating an important pitfall for assessment.

put of a test-performance and the functional status of the system. It is argued here that reality is much more complex; the level of functional reorganization is not fully or solely reflected in the 'pure' end-result of a task, but also in the decreasing (or increasing) compensatory costs across time. We argue here that assessment procedures should be sensitive to this phenomenon because otherwise the dynamical changes underlying the observable end-result will be missed, often leading to the unjustified conclusion that no improvement has taken place, or to the (even more damaging) conclusion that no pathology exists. The latter conclusion is notorious in the cases of insidious neurological disease.

In the remainder of this text it will be shown that this thinking in terms of compensatory costs can be used for the development of novel assessment techniques, relevant for orthopaedics, rheumatology, neurology, rehabilitation medicine, and psychology.

5. Compensation and adaptation

There is more to say about the principle of output optimization. In a healthy motor system 'commands' are sent to effector systems; afferent information is fed back to brain centres and normally no discrepancy exists between the efferent 'commands' and the afferent information. The system 'knows' what to expect. Hence, in these cases an efferent-afferent equilibrium exists. Now look what happens when the system is damaged by a lesion to one of the effector systems. After a short period of immobility (e.g. due to pain) compensatory motor patterns emerge (more or less in the same way as walking at the lateral foot-sole emerges as a result of a sharp stone in the shoe). These compensatory patterns, however, create a novel flow of afferent information, largely unknown to the central networks. Our point is that when these compensatory motor patterns last for a certain time, central networks will change. Indeed, they will accept the compensatory pattern as the new norm.

The main advantage of such a compensatory change is that the discrepancy between efferent and afferent streams of information decreases relatively fast. This is important since the discrepancy makes the system very vulnerable.

It is argued here that as long as the reorganization is not completed the performance of motor acts becomes highly cognitive and visually controlled. What we attempt here is to translate the above discussed changes at the neuro-physiological level to the level of motor behavior. Indeed, as long as the neural maps are not fully adapted to the novel lay-out of peripheral information, the system is forced to exploit other control-routes.

6. Two important aspects of functional reorganization

Functional reorganization or recovery is for a large part dependent on the ability of the central nervous system to adapt to changes. Hence, the study of reorganization is the study of adaptation. But how can this adaptive process be studied, what observable mechanisms can be distinguished? From the work that was performed during the last 10 years, two aspects with a strong predicting power towards functional recovery can be distilled [1,7,45]. These aspects are (1) a decrease of cognitive involvement across time; and (2) a decrease of visual dependency across time.

6.1. Decrease in cognitive involvement

Skilled typists can repeat what is said to them while at the same time typing a text unrelated to this verbal message [46]. With enough training, college students can read while writing down words presented to them at the same time [47]. Also many normal daily life activities take place without noticeable attention or conscious control. As a result of a long learning process the performance of these activities is more or less automated, so that less higher level involvement is needed for control. However, after damage this automaticity is lost. Although the execution of motor acts often is still possible, a substantial price has to be paid in terms of costs of compensation. The level of these costs can be measured by using dual-tasks.

The basic idea behind the dual-task methodology is that the performance of a difficult (non-automated) task produces interference with other simultaneously performed tasks [48]. Hence, by employing an attention demanding task, it is possible to use the degree of interference of this task with the primary task (e.g. standing or walking) as a measure of the attention demands (cognitive regulation) of the primary task. In spite of the long history of this idea and although the relevance seems clear, it has, until now, seldom been used in clinical (movement) analysis or in neurological assessment. So, if two tasks can be performed as well simultaneously as separately, then at least one task seems to be automatic. On the other hand, if a task (e.g. walking) is performed worse when it is combined with a secondary task (e.g. talking), then both tasks must be non-automatic. The worsening of the primary task as a result of the simultaneous performance of a secondary task is termed a *dual-task interference effect*. If non-automaticity is reflected by a large dual-task interference effect and automaticity by a low (or even absent) dual-task interference effect then measuring dual-task interference across time should give a valid indication of the level of (returning) automaticity.

Many motor control theories assume such a transition from attention-invested or controlled performance (slow mode) to attention-free or automatic performance (fast mode) during the learning of a novel skill [49–51]. Recently these ideas have been applied in studies focusing on disorders of motor control in the elderly [52–54], and a very elegant application can be found in Lundin-Olson [55] who used a very simple dual task procedure to predict falling in elderly people. In spite of these applications the use of dual-task methodology in rehabilitation-research is, until now, rare.

6.2. Decrease in cognitive involvement: experimental evidence

In a series of experiments [56–61] the validity of this idea was tested. The experiments were focused on the recovery of balance after lower limb amputation (above-knee as well as below-knee amputations). Recall that amputation leads to a massive disruption of afferent-efferent equilibrium and forces the central nervous system to develop alternative control strategies. As long as these novel strategies are not available the system remains dependent on compensatory strategies and very vulnerable. The basic experiment went as follows: subjects with a leg amputation and wearing their (first) prosthesis were instructed to stand as still as possible on a force platform with the hands folded at the back. The centre-of-pressure was registered. It could be observed that, even in the very beginning of the rehabilitation process, patients were able to perform this task; their balance performance differed not significantly from healthy age-matched controls. After 10 s a slide was projected in front of the subject with the words 'RED', 'BLUE', 'GREEN', etc. The words, however, were printed in an ink which deviated from the semantics of the words, so that the word 'RED' was printed in blue, the word 'BLUE' was printed in green, etc. The patients were instructed to name as fast as possible the color of the words and to suppress the very strong tendency to read the words. This is an attention demanding task and the question was whether this task would interfere with the ability of the patient to maintain its upright balance. The results indicated that in the beginning of the rehabilitation process the balance performance of patients was significantly hindered by the performance of a concurrent cognitive task (see Fig. 2, upper graph). Such a dual-task interference effect could not be shown in a group of healthy age-matched control subjects.

The interesting point, however, was that this interference effect slowly diminished across time, indicating a re-automatization of balance control (see Fig. 2, lower graph).

These results can not be explained in terms of structural interference or outcome conflicts [62]. Indeed,

outcome conflicts refer to the fact that the produced outputs hinder each other, in that they change the state of some variable that is relevant for the performance of the concurrent task. It is hard to see in what form the fast identification of inks could hinder (in structural terms) the control of upright balance, although the task in itself, of course creates an outcome conflict. Neither can the data be explained in terms of the specific interference that appears between similar tasks or to the effects of spatial compatibility or to the homology of the co-activated response organs. Hence, some form of central interference is suggested, because, due to the peripheral lesion, the normal fast (automatic) mode of control cannot be employed, so that the system is forced to shift to a slow mode of control.

One of the essentials of an amputation, however, is its acute character, so that the system suddenly is deprived from the input of a relevant effector organ (e.g. hand, arm, leg). An interesting question therefore is whether this dual-task effect also would appear in patients with a slowly progressing chronic disease leading to balance disturbances. The above described experiment was therefore repeated in patients with HMSN (Hereditary Motor and Sensory Neuropathy), type I. These patients generally have distal muscle weakness, atrophy and loss of somatesthesis, especially of deep sensibility. Also foot-ankle deformities such as *pes cavus*, *transversoplanus*, *equinovarus* and *hammer toes* may by observed [58,59]. Problems in postural control are one of the most frequent consequences of HMSN. The results showed, however, that although these patients clearly suffered from balance disorders they were not hindered by the dual-task performance, indicating that due to the slowly progressing character of the disease the brain had ample time to reorganize its control procedures and to create a novel efferent-afferent equilibrium (see Fig. 3, upper graph).

Now, let us take the next step. What would happen if these patients were fitted with corrective orthopaedic footwear? The results were surprising. It was shown that although dual-task performance had no effect on balance control in barefoot conditions, balance control was (temporarily) significantly hindered in conditions when the patients were wearing new orthopedic footwear (see Fig. 3, lower graph). Although at first sight this result seems remarkable, it is perfectly in accordance with the above described 'fluid' character of the central nervous system and underscores the permanent adaptive character of (motor) control. Indeed, as soon as movement constraints are changed by the shoes the system is forced to adapt and to shift to another control strategy, which is less automated thus leading to a dual-task interference effect.

In a study of De Visser et al. [61] the dual-task methodology was used in order to get more insight into the recovery of gait after limb saving surgery in patients with malignant bone tumors. The study was focused on
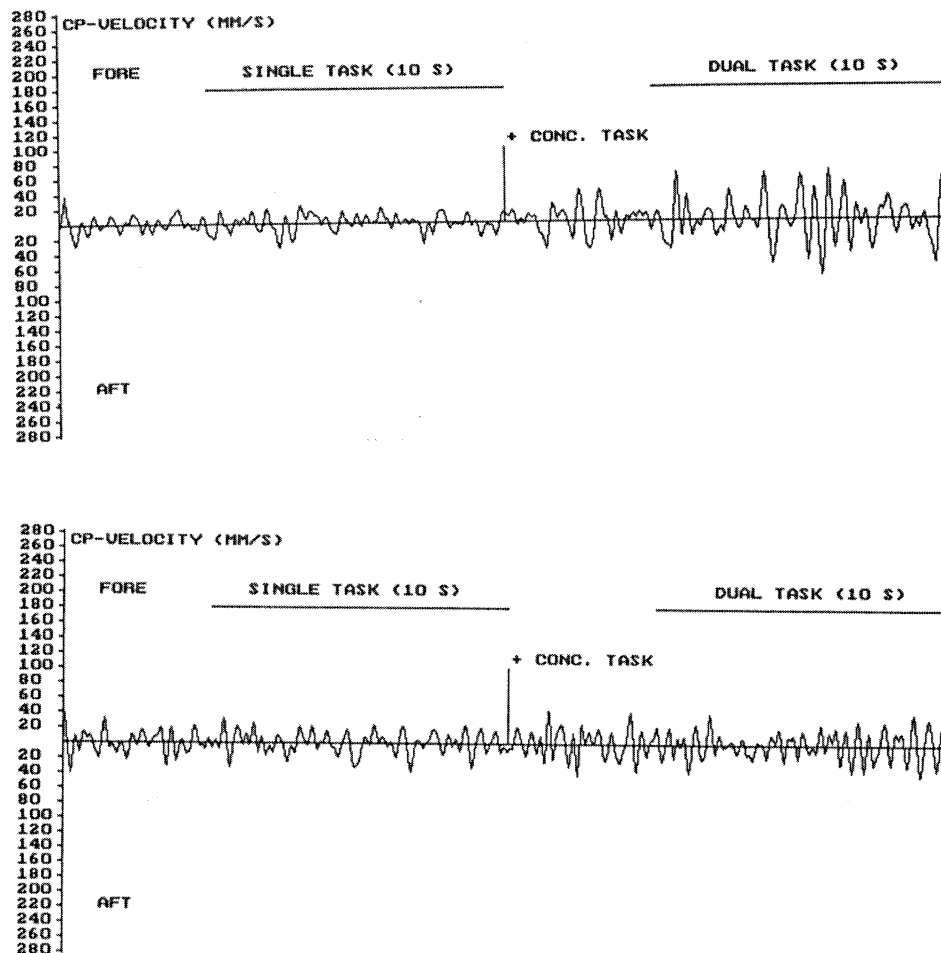
Fig. 2. The upper graph shows a balance registration (fore-after sway) of one of the amputees at the start of rehabilitation. Note the difference between the single and dual task performance. The lower graph shows a balance registration of the same amputee at the end of rehabilitation. Note the improvement of the dual-task performance. Figures reprinted from Ref. [77].

reautomatization of gait. The main outcome measures were walking speed and stride time duration. The results showed that although restoration of gait after surgery was impressive, it was not automated, so it broke down under conditions of visual and cognitive load.

6.3. Decrease in visual dependency

Normally somesthetic input from the periphery is received, interpreted and acted on appropriately while moving. However, when somatosensory input is distorted or absent, the 'weight' of this type of peripheral input decreases and vision, as a result of a strategic shift, becomes the most important input-source. Indeed, the system can no longer 'build' on the incoming somesthetic information since this information has lost its redundant character. It can therefore be predicted that in the early rehabilitation phase patients will show a marked visual dependency. What is meant here is a disproportional dependency. Indeed, we are always us-

ing (on line) visual information and vision provides predictive information for prospective control of gait [63–67], but and this is important, we are not using this information *all the time* to guide us and to control the action. We all are aware that it is possible to take one's eyes of the trajectory while walking without falling down or becoming disoriented. So it is the degree of dependency that matters and it is argued here that in patients with sensorimotor disorders this dependency becomes disproportionally large. The interesting question is whether the amount of visual dependency changes across time in the same way as the cognitive dependency did.

6.4. Decrease in visual dependency: experimental evidence

To answer this question postural control was assessed in patients with a unilateral leg amputation before and after a conventional rehabilitation training program. The experimental set-up was basically the

same as employed in the above mentioned studies, that is, the centre-of-pressure fluctuations during quiet upright standing on a force-platform were registered with and without visual information. The results indicated that besides a small, but non significant improvement in balance control with full visual information, there was a significant improvement of balance control without vision, indicating a decrease in visual dependency across time [56,57]. The visual-dependency scores approached normal values at the end of the rehabilitation. This decrease in visual dependency can be seen as a (indirect) reflection of a

central re-integration of sensory input from the amputated limb into the multi-sensory control of posture. This conclusion is important since it again indicates that relevant aspects of the recovery process remain hidden for the observer as long as specific test manipulations are not used.

7. Age-dependency of adaptation

The present paper focuses on the flexibility of the human motor system and on the capacity to adapt
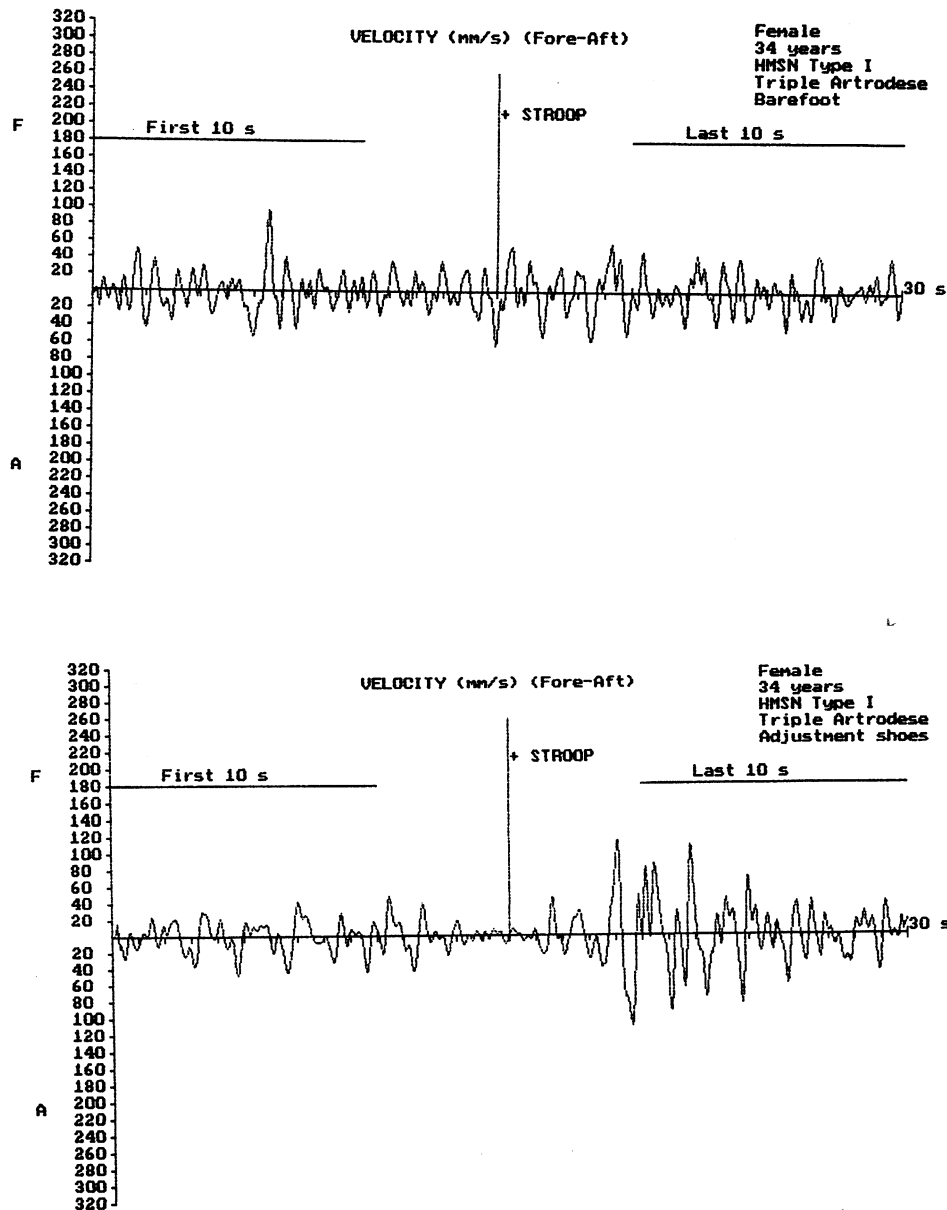

Fig. 3. The upper graph shows a patient with HMSN standing on a force platform during a single task and a dual-task condition. Note that, although the balance performance is impaired in terms of an increased fore-after sway, the introduction of the dual-task does not affect performance. The lower graph shows the same patient standing on a force platform. The patient is now wearing orthopaedic footwear. Note that in the single task condition the balance performance has improved but that in the dual-task condition the footwear causes a substantial dual-task effect leading to an increased fore-after sway. Figures are unpublished figures from Ref. [59].

continuously to the actual situation. It is an interesting question whether this capacity changes with age, and whether the elderly are more hindered by increasing task-complexity and by a non-optimal neuro-motor system then the younger adults. In other words, are the costs of compensation higher in the elderly compared to a younger group? In this section, this topic will be discussed.

It is known that older people are less able to prepare motor programs in advance of imperative stimuli when the preceding warning stimuli bear no obvious relation to the task demands, even though the warning stimuli do in fact contain relevant information. Hence, older people seem to be less flexible and adaptive than younger people [68]. It is also known that older people are slower, and early theories stated that the elderly were slower due to peripheral sensory factors interfering with performance. Birren and Botwinick [69] performed a classical study in which they examined the simple reaction times of the jaw, finger and foot to an auditory signal. They argued that if the locus of slowing was peripheral then there would be a statistical interaction between age and the more distal effector. However, if slowing were a central phenomenon, then an additive effect would result. Since the latter outcome was found support was claimed for the central locus of age-related slowing. More recently Stelmach and Worringham [70], showed that the decreased stability with increasing age is the result of a slowing of the central integrative mechanisms. Similar arguments can be found in the work of Teasdale et al. [71] who showed that postural adjustments in the elderly required cognitive processing. They altered the visual and surface conditions to determine if attentional resources were needed to be allocated to the postural task when there was a reduction of the available sensory information. Their results showed that as the sensory information decreased, the postural tasks became increasingly difficult for the elderly and required more of their attentional capacity.

Other evidence for a central source for the decrease in stability comes from the work of Woollacott et al. [72]. Elderly and young adults were submitted to various conflicting sensory conditions that were created by rotating the surface platform and visual surround in proportion to the subject's sway thus making these sources of sensory information inappropriate for the postural task. The results showed that the elderly were much more affected by the combined visual and proprioceptive conflicting conditions than were the young. In a more recent study [53], Teasdale, Bard, Dadouchi, Fleury, Larue and Stelmach showed that after a period without vision, the elderly persons were unable to adapt rapidly to the visual information which suddenly became available. In other words, the ability of the system to shift rapidly and smoothly between different control modes seems to be impaired in the elderly. Besides, the results showed that as sensory information decreased, the postural task became more difficult for the elderly and required more of their processing capacity. The latter aspect would explain the observation that it is increasingly difficult for the elderly to perform two tasks at once.

Mulder et al. [54] addressed the question of whether elderly were impaired in their capacity to adapt rapidly to disturbed peripheral conditions. In their study normal young adults and healthy elderly subjects, between 60 and 85 years, recruited from a dancing-club, had to walk on a walkway. There were four gait conditions: (1) simple unobstructed gait (single task); (2) walking while solving a mental calculation task (dual task); (3) walking while wearing flippers; and (4) flipper-walking while performing the mental calculation task. The results were interesting and showed that young adults were only minimally hindered by the dual-task condition in combination with flipper walking. The elderly (> 70 years), however, were substantially hindered by the dual-task condition and showed significant gait impairment in the dual task plus flipper condition. Admitted, the subjects in our flipper experiment were not followed across time to determine the effects of learning, so it may be that after training the age-dependent effects would have disappeared. But that is not the point here, the main aim was to indicate that elderly react different to peripheral manipulations than young adults. The results indicated that their immediate sensorimotor adaptability seemed to be less 'smooth' than in the young. Recall, that these were totally healthy and active elderly, living alone and independently.

These results have implications for the application of orthotic devices. Patients normally are fitted with orthotic devices primarily from a biomechanical perspective. Independently of age it is expected that these subjects are able to employ these devices, fully integrated with their activities of daily living. Although it is well known that many patients have difficulties in employing these orthopedic devices, no studies are known to us which focus on the (central) computational consequences of peripheral mechanical aids. Normally this field is the domain of rehabilitation engineers and not of behavioral scientists or motor control experts.

The results of these studies seem to indicate that aging impairs the ability to shift between different control modes. This has clear implications for our understanding of recovery processes since it would mean that elderly do not adapt optimally to changing internal and external conditions. This necessitates further study on the age-related interaction between peripheral and central processes in order to get more insight into the role of adaptation in the recovery process.

8. Conclusions

The present article pictured, in rather rough terms, important aspects of the adaptive capacity of the human *cognito-sensori-motor system*. We argued that these aspects have implications for the assessment of functional recovery. Indeed, if the principle of output optimization forms an emergent characteristic of the system, then solely observing the manifest outcome of diagnostic tasks without taking into account the compensatory effort necessary to reach the end-result is not without risks, especially when these results are obtained by means of very simple tasks to be performed in an optimal (laboratory- and/or hospital) environment. Most of the employed test-situations give the subjects ample opportunity to compensate for their deficits by shifting toward other control strategies (e.g. visual and/ or cognitive regulation of task performance). As a result of this adaptive shifting, which may take place without any awareness of the patient, the effects of pathology remain unnoticed. These remarks are especially relevant for the diffuse or mild disorders or for the early stages of a disease process and they picture an important pitfall for assessment. Indeed, in these cases deviations from the norm will be found only under novel or more complex ('real-life') conditions and exactly such conditions are lacking in most of the laboratories for clinical movement analysis. The latter argument has been confirmed in a survey among 32 (European) laboratories for clinical gait analysis [73]. It was indicated that 29 laboratories used straight level walking in a well lit environment without any hindrances, although eight of these laboratories reported walking on an inclined plane and four reported walking on different textures. In only five (of these) laboratories the tasks were combined with other tasks, such as a memory task or mental arithmetic. The three remaining laboratories were excluded from the study since they solely focused upon analysing upper extremity tasks.

Hence, in most of the 'assessment environments' it is impossible to determine the aspects of recovery as discussed in the present paper, which might partly explain the often mentioned lack of relevance of (advanced) movement analysis techniques for predicting functional behavior [74–76].

It is, therefore, important to develop novel assessment procedures by means of which clinicians are able to measure the course of *functional recovery*. In the present article it is argued that a decrease in cognitive regulation and a decrease in visual dependency form important and measurable ingredients of functional improvement in that they reflect the process of re-automatization. Indeed, when sensory, motor, and cognitive processes continuously interact in the regulation of functional motor behavior, it seems plausible that these processes and their changing interactions should play a role also in assessment methods that pretend to measure functional improvement. At this moment this is clearly not the case, as the majority of motor assessment procedures focus at the level of impairments.

References

[1] Mulder T, Nienhuis B, Pauwels J. The assessment of motor recovery: a new look at an old problem. J Electromyogr Kinesiol 1996;6:137–45.

[2] Luria AR. The Working Brain. New York: Basic Books, 1973.

[3] Mulder T, Hochstenbach JBN, (in press). Motor Control and Learning: Implications for Neurological Rehabilitation. In: Greenwood R, Barnes MP, McMillan TM, Ward CD (Eds). The Handbook of Neurological Rehabilitation. Sussex: Psychology Press.

[4] Mulder T. A process-oriented model of motor behavior: towards a theory-based rehabilitation approach. Phys Ther 1991;71:157–64.

[5] Mulder T. Current ideas on motor control and learning: implications for therapy. In: Illis L, editor. Spinal Cord Dysfunctions: Vol. II: Treatment. Oxford: Oxford University Press, 1992:187–209.

[6] Mulder T. Current topics in motor control: implications for rehabilitation. In: Greenwood RJ, Barnes MP, McMillan TM, Ward CD, editors. Neurological Rehabilitation. Edinburgh: Churchill Livingstone, 1993:25–133.

[7] Mulder T, Geurts ACH. Recovery of motor skill following nervous system disorder: a behavioral approach. Bailliere's Clin Neurol 1993;2:1–13.

[8] Lashley KS. The problem of serial order in behavior. In: Jeffress LA, editor. Cerebral Mechanisms in Behavior. New York: Wiley, 1951:112–36.

[9] Glencross DJ. Motor control and sensory-motor integration. In: Glencross DJ, Piek JP, editors. Motor Control and Sensory-Motor Integration: Issues and Directions. Amsterdam: North Holland, 1995:3–7.

[10] Kugler PN, Scott Kelso JA, Turvey MT. On the concept of coordinative structures: I. Theoretical Lines of convergence. In: Stelmach GE, Requin J, editors. Tutorials in Motor Behavior. Amsterdam: North Holland, 1980:3–47.

[11] Bernstein N. The Co-ordination and Regulation of Movement. London: Pergamon Press, 1967.

[12] Jordan M, Rosenbaum DA. Action. In: Posner MI, editor. Foundations of Cognitive Science. Cambridge, MA: MIT press, 1989:727–67.

[13] Singer W. The organization of sensorimotor representations in the neocortex: a hypothesis based on temporal coding. In: Umilta M, Moscovitch M, editors. Conscious and Nonconscious Information Processing. Attention and Performance XV. Cambridge Mass: MIT press, 1994:77–107.

[14] Kosslyn SM, Koenig O. Wet Mind: the New Cognitive Neuroscience. New York: The Free Press, 1992.

[15] Reeke GN Jr, Sporns O, Edelman G. Synthetic neural modeling: comparisons of population and connectionist approaches. In: Pfeifer R, Schreter Z, Fogelman-Soulie F, Steels L, editors. Connectionism in Perspective. Amsterdam: Elsevier Publ, 1989:113–39.

[16] Plotkin H. The Nature of Knowledge: Concerning Adaptations, Instinct and the Evolution of Intelligence. London: Allen Lane, 1994.

[17] Stelmach GE, Homberg V. Sensorimotor Impairment in the Elderly. Dordrecht: Kluwer Publ, 1993.

[18] Duysens J, Trippel M, Horstmann GA, Dietz V. Gating and reversal of reflexes in ankle muscles during human walking. Exp Brain Res 1990;82:351–8.

[19] Dietz V, Zijlstra W, Duysens J. Human neuronal interlimb coordination during split-belt locomotion. Exp Brain Res 1994;101:513–20.

[20] Zijlstra W, Dietz V. Adaptability of the human stride cycle during split-belt walking. Gait Posture 1995;3:250–7.

[21] Prokop T, Berger W, Zijlstra W, Dietz V. Adaptational and learning processes during human split-belt locomotion: interaction between central mechanisms and afferent input. Exp Brain Res 1995;106:449–56.

[22] Bach-y-Rita P. Brain plasticity. In: Goodgold J, editor. Rehabilitation Medicine. St. Louis: Moshby, 1988:113–8.

[23] Lashley KS. Temporal variation in the function of the gyrus precentralis in primates. Am J Physiol 1923;65:585–602.

[24] Hubel DH, Wiesel TN. The period of susceptibility to the physiological effects of unilateral eye closure in kittens. J Physiol 1970;206:419–36.

[25] Merzenich MM, Kaas JH. Reorganization of mammalian somatosensory cortex following peripheral nerve injury, TINS 1982;434–436.

[26] Kaas JH, Merzenich MM, Killackey HP. The reorganization of somatosensory cortex following peripheral nerve damage in adult and developing animals. Annu Rev Neurosci 1983;6:325–56.

[27] Hall EJ, Flament D, Fraser C, Lemon RN. Non-invasive brain stimulation reveals reorganized cortical outputs in amputees. Neurosci Lett 1990;116:379–86.

[28] Hess CW, Mills KR, Murray NMF. Magnetic stimulation of the human brain: facilitation of motor responses by voluntary contraction of ipsilateral and contralateral muscles with additional observations on an amputee. Neurosci Lett 1986;71:235–40.

[29] Cohen LG, Bandinelli S, Findley TW, Hallett M. Motor reorganization after upper limb amputation in man: a study with focal magnetic stimulation. Brain 1991;114:615–27.

[30] Topka H, Cohen LG, Cole RA, Hallett M. Reorganization of corticospinal pathways following spinal cord injury. Neurology 1991;41:1276–83.

[31] Cohen LG, Topka H, Cole RA, Hallett M. Leg paresthesias induced by magnetic brain stimulation in patients with thoracic spinal cord injury. Neurology 1991;41:1283–8.

[32] Roelcke U, Curt A, Otte A, Missimer J, Maguire RP, Dietz V, Leenders KL. Influence of spinal cord injury on cerebral sensorimotor systems: a PET study. J Neurol, Neurosurg Psychol 1997;62:61–5.

[33] Brasil-Neto JP, Cohen LG, Pascual-Leone A, Jabir FK, Wall RT, Hallett M. Rapid reversible modulation of human motor outputs after transient deafferentation of the forearm: a study with transcranial magnetic stimulation. Neurology 1992;42:1302–6.

[34] Brasil-Neto JP, Valls-Sole J, Pascual-Leone A, Cammarota A, Amassian VA, Cracco R, Maccabee P, Cracco J, Hallett M, Cohen LG. Rapid modulation of human cortical motor outputs following ischaemic nerve block. Brain 1993;116:511–25.

[35] Traversa R, Cicinelli P, Bassi A, Rossini PM, Bernardi G. Mapping of motor cortical reorganization after stroke: a brain stimulation study with focal magnetic pulses. Stroke 1997;28:110–7.

[36] Dubner R, Ruda MA. Activity-dependent neuronal plasticity following issue injury and inflammation. TINS 1992;15:96–102.

[37] Spear PD. Behavioral and neurophysiological consequences of visual cortex damage. In: Sprague JM, Epstein AN, editors. Progress in Psychobiology and Physiological Psychology, 8. Orlando: Academic Press, 1977:45–83.

[38] Cohen LG, Weeks RA, Sadato N, Celnik P, Ishii K, Hallett M. Period of susceptibility for cross-modal plasticity in the blind. Ann Neurol 1999;45:451–60.

[39] Calford MB, Tweedale R. Interhemispheric transfer of plasticity in the cerebral cortex. Science 1990;249:805–7.

[40] Edelman GM. Neural Darwinism: The Theory of Neuronal Group Selection. New York: Basic Books, 1987.

[41] Pascual-Leone A, Torres F. Plasticity of the sensorimotor cortex representation of the reading finger in Braille readers. Brain 1993;116:39–52.

[42] Jenkins WM, Merzenich MM, Ochs MT, Allard T, Guic-Robles G. Functional reorganization of primary somatosensory cortex in adult owl monkeys after behaviorally tactile stimulation. J Neurophysiol 1990;63:82–104.

[43] Bach-y-Rita P. Brain Mechanisms in Sensory Substitution. New York: Academic Press, 1972.

[44] Waters RL, Mulroy S. The energy expenditure of normal and pathologic gait. Gait Posture 1999;9:207–31.

[45] Mulder T, Nienhuis B, Pauwels J. Prediction of independent mobility following damage to the nervous system. In: Friess W, editor. Ambulante und Teilstationare Rehabilitation von Hirnverletzten. Munchen: Zuckschwerdt Verlag, 1996:52–60.

[46] Shaffer LH. Multiple attention in continuous verbal tasks. In: Rabbit PM, Dornic S, editors. Attention and Performance, V. London: Academic Press, 1975:157–67.

[47] Spelke E, Hirst W, Neisser U. Skills of divided attention. Cognition 1976;4:215–30.

[48] Wickens CD. Processing resources in attention. In: Parasuraman R, Davies DR, editors. Varieties of Attention. Orlando: Academic Press, 1984:63–102.

[49] Adams JA. A closed-loop theory of motor learning. J Mot Behav 1971;3:111–49.

[50] Fitts PM, Posner MI. Human Performance. Monterey: Brooks/Cole, 1967.

[51] Fitts PM. Perceptual-motor skill learning. In: Melton AW, editor. Categories of Human Learning. New York: Academic Press, 1964.

[52] Teasdale N, Lajoie J, Bard C, Fleury M, Courtemanche R. Cognitive processes involved for maintaining postural stability while standing and walking. In: Stelmach GE, Homberg V, editors. Sensorimotor Impairment in the Elderly. Dordrecht: Kluwer Publ, 1993:157–68.

[53] Teasdale N, Bard C, Dadouchi F, Fleury M, Larue J, Stelmach GE. Posture and elderly persons: evidence for deficits in the central integrative mechanisms. In: Stelmach GE, Requin J, editors. Tutorials in Motor Behavior II. Amsterdam: North Holland, 1992:917–31.

[54] Mulder T, Berndt H, Pauwels J, Nienhuis B. Sensorimotor adaptability in the elderly and disabled. In: Stelmach GE, Homberg V, editors. Sensorimotor Impairment in the Elderly. The Hague: Kluwer Academic Publishers, 1993:413–26.

[55] Lundin-Olsson L. 'Stops walking when talking' as a predictor of falls in elderly people. Lancet 1997;349:617.

[56] Geurts ACH, Mulder T, Nienhuis B, Rijken RAJ. Dual-task assessment of reorganization of postural control in persons with lower limb amputation. Arch Phys Med Rehabil 1991;72:1059–64.

[57] Geurts ACH, Mulder T, Nienhuis B, Rijken RAJ. Postural reorganization following lower limb amputation: possible motor and sensory determinants of recovery. Scand J Rehabil Med 1992;24:83–90.

[58] Geurts ACH, Mulder T, Nienhuis B, Rijken RAJ. Postural organization in patients with hereditary motor and sensory neuropathy. Arch Phys Med Rehabil 1992;73:569–72.

[59] Geurts ACH, Mulder T, Nienhuis B, Rijken RAJ. Influence of orthopaedic footwear on postural control in patients with hereditary motor and sensory neuropathy. J Rehabil Sci 1992;5:3–9.

[60] Geurts ACH, Mulder T. Attention demands in balance recovery following lower limb amputation. J Mot Behav 1994;26:162–70.

[61] De Visser E, Pauwels J, Duysens J, Mulder Th, Veth RPH. Gait adaptations during walking under visual and cognitive constraints: a study of patients recovering from limb-saving surgery of the lower limb. Am J Phys Med Rehabil 1998;77:503–9.

[62] Navon D, Miller J. Role of outcome conflict in dual-task interference. J Exp Psychol 1987;13:435–48.

[63] Laurent M, Thomson JA. The role of visual information in control of a constrained locomotor task. J Mot Behav 1988;20:17–37.

[64] Thomson JA. Is continuous visual monitoring necessary in visually guided locomotion? J Exp Psychol Hum Percept Perform 1983;9:427–43.

[65] Patla AE. In search of laws for the visual control of locomotion: some observations. J Exp Psychol Hum Percept Perform 1989;15:624–8.

[66] Patla AE, Robinson C, Samways M, Amstrong CJ. Visual control of step length during overground locomotion: task specific modulation of the locomotor synergy. J Exp Psychol Hum Percept Perform 1989;15:603–17.

[67] Bardy BG, Baumberger B, Fluckiger M, Laurent M. On the role of global and local visual information in goal-directed walking. Acta Psychol 1992;81:199–210.

[68] Canavan AGM, Bayer N, Lutzenberger W. The decline of spatial and temporal abilities with age. In: Stelmach GE, Homberg V, editors. Sensorimotor Impairment in the Elderly. Dordrecht: Kluwer, 1993:57–72.

[69] Birren JE, Botwinick J. Speed of response as a function of perceptual difficulty and age. J Gerontol 1955;10:433–6.

[70] Stelmach GE, Worringham CJ. Sensorimotor deficits related to postural stability: implications for falling in the elderly. Clin Geriatr Med 1985;1:679–94.

[71] Teasdale N, Bard C, LaRue J, Fleury M. On the cognitive penetrability of postural control. Exp Aging Res 1992;19:1–13.

[72] Woollacott MH, Shumway-Cook A, Nashner LM. Aging and posture control: changes in sensory organization in muscular coordination. Int J Aging Hum Dev 1986;23:97–114.

[73] Pauwels J, Mulder T. Current tasks in the assessment of gait and balance. Internal report related to European Project CAMARC-II (project A-2002), Deliverable 26, part A. Roma: Instituto Superiore di Sanita, 1994.

[74] Messenger N, Bowker P. The role of gait analysis in clinical medicine: a survey of UK centers. Eng Med 1987;16:221–7.

[75] Rozendal RH. Gait analysis and ICIDH. J Rehabil Sci 1989;2:89–93.

[76] Wade DT. Assessment of motor function: impairment and disability. In: Greenwood R, Barnes MP, McMillan TM, Ward CD, editors. Neurological Rehabilitation. Edinburgh: Churchill Livingstone, 1993:147–63.

[77] Geurts ACH, Mulder Th, Nienhuis B, Rijken R. From the analysis of movements to the analysis of skills: bridging the gap between the laboratory and the clinic. J Rehabil Sci 1991;4:9–12.