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Neuromuscular Skeletal Plasticity Moving on from Traditional Physiotherapy Concepts

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<Abstract>

Purpose : N.A.P.(Neuromuscular Skeletal Plasticity) an integrative neuro-orthopedic concept to facilitate motor strategies in daily life. The primary thesis is, that treatment of body functions and structural impairments should be integrated within goal-oriented activities. The purpose of this article is to demonstrate that the functional activity itself, determines the structure.

Material and Methods : A case report of a dentist with brachial plexus lesion after a motor vehicle accident is presented. The necessity for training body functions within relevant tasks is undermined by references which emphasize the importance of training realistic activities to enhance long-term changes in neural representation.

Results : The treatment methods presented in this case show significant effects for the patient´s ability to participate in his profession within less than a year´s time after his motor vehicle accident.

Conclusions : Current evidence supports the treatment methods of this concept. The inability to flex his elbow and supinate his forearm placed a considerable doubt to his ability to ever be able to participate in his profession again. Structural reorganization is possible and depends on functional demands, which need to be trained task-specifically. Single case reports may serve as the basis for further randomized controlled studies to support the efficacy of the treatment methods within the N.A.P. concept.

Key Words : Brachial plexus lesion, Mirror neurons, Plasticity, Motor learning, Manual therapy, Habituation

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Introduction

Plasticity means change, or "development."

In this article an integrative neuro-orthopedic concept to facilitate motor strategies in daily life is presented. The main *philosophy* of this concept is that (functional) activities determine the body function and structure. Treatment of structural impairments, such as limited joint mobility, joint stability or muscle weakness needs to be integrated within the goal-oriented activity itself. It is not done as a preparation for the activity.

Treatment *principles* which underly the treatment methods and techniques of this concept incorporate knowledge of traditional manual therapy concepts, pertaining to biomechanics and neurodynamics with neurophysiological knowledge, which has its origin in the traditional neurophysiological concepts. Biomechanical and neuroscientific knowledge underlies a constant flow, as medical-technical development continues.

Learning requires experiencing meaningful activities.

Within the N.A.P. concept, the therapist's hands are used as a tool to attain the best possible biomechanical situation in which the movement would occur under healthy circumstances. In doing so, the neuromuscular coordination required for the specific task can be facilitated. This way the brain gets an "idea" of the movement and planing the movement may become easier. Since joint positions and muscle activation patterns are neither perceived, nor controlled consciously, specific tactile information applied, within the goal oriented activity, can enable the patient to experience his movements, without fear or pain. Automatizing of these positive movement experiences is achieved by coaching the patient in doing self-exercises, which are oriented towards his individual needs. Ideally, the patient will learn to perform these actions independently.

Traditional Concepts

The paradigm of the 80 and early 90s of Manual Therapy was that passive mobilization of joint structures sufficed to restore normal functional activity. Structural treatment, to avoid or to treat limitations in range of motion is fundamental to many Manual Therapy concepts (e.g. Maitland, Kaltenborn-Evjenth, McKenzie). The tests and treatment procedures are mainly passive. The therapist mobilizes the joints with traction and gliding techniques, oscillations and muscle stretching techniques, which are mainly passive. Facilitation concepts (e.g. Bobath, PNF, Vojta) follow the goal to enhance neuromuscular coordination by use stimuli, mainly tactile. Tactile input was often used to initiate movement.

As long as voluntary action is not possible, these methods may be very appropriate to avoid contractures and muscle atrophy. Within the N.A.P. concept, information is used to cause central changes which, in turn, lead to peripheral changes. The patient is encouraged to focus his attention on the information pertaining to the task. His search for the appropriate strategy is assisted by the therapist, possibly also tactile.

The general hypothesis underlying the methods of this concept is that long-term changes may be attained, if structures and body functions are trained during the execution of or by envisioning realistic activities.

Clinical observation has shown that therapy at the impairment level doesn't necessarily carry over to the activity and participation levels automatically (International classification of function (ICF) (Fheodoroff, 2007)). This undermines the necessity for developing new treatment methods which may cause long-term, relevant changes.

Principles which determine the methods of the N.A.P. Concept:

1. Structures are determined by the (func-tional) activity.
2. Each structure is prepared to take on the loads only for which they have been trained.

Ⅰ. Plasticity

The basis for the treatment methods, is the idea of "Plasticity," which may defined as the ability to adapt to functional demands. When tasks vary or environmental conditions change, then variability in patterns of interconnections within the sensory and motor systems, as well as changes in the effectiveness of neural connections, are required for learning (Kandel, 2000).

A. Neural Plasticity:

Many collateral connections within the brain allow variability according to behavioral needs(Edelman, 1987). Depending on use, receptors show plasticity, which leads to stronger or weaker synaptic transmission. If certain body parts aren't used due to weakness, chronic pain or even because of fear, changes in representation fields within the cortex can be determined (Forderreuther 2004, Pasqual-Leone et al. 1993, Zanette et al. 1997, Flor et al. 1995, Maihofner et al. 2003).

What you don't use, you lose!

Merznich et al.(1984) showed in his studies with monkeys that depending on use, changes in representation occur. Body parts which aren't used lose representation fields, which are taken over by those, which are used more.

Ramachandran(1993) discovered that following amputation, subjects actually "felt" their lost hand in their face and shoulder area (Fig. 2). The loss of afferent information can cause unpleasant sensations, such as phantom pain. He had the idea to give the patient the representation of his lost hand back by using a mirror for visual input.

The recent discovery of so-called "mirror neurons" offers a possible explanation for the importance of visualizing realistic movements

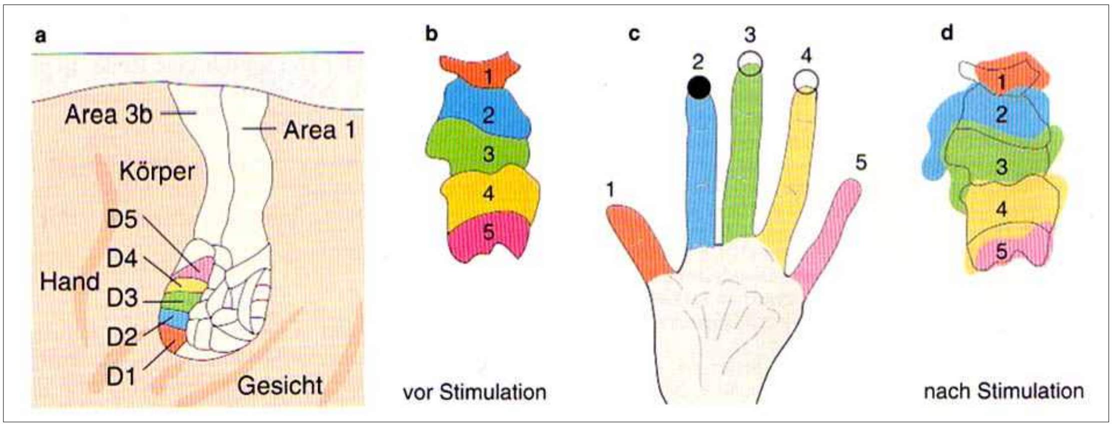

Fig. 1. Reorganization of the somatosensory receptive areas after training. Monkeys turned a disc 1 hour a day for a duration of 3 months. The receptive fields are shown before and after training.

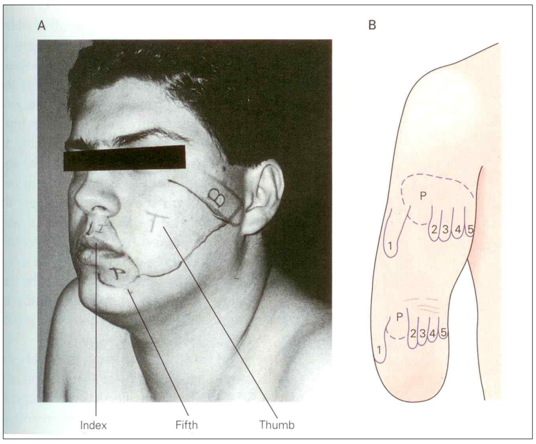

Fig. 2. Phantom pain can be produced by stimulating the face.

which cannot be performed actively. Experiencing the activity accompanied by the therapist's manual guidance can help the patient to "get the picture" or gain knowledge about the characteristics of the movement ("Knowledge of Performance", "Knowledge of Results", Schmidt, 1999).

The Mirror Neuron System is located in premotor areas, which organize the coordination (timing) of muscle synergies, required for the desired action. These areas are also responsible for selecting relevant information needed to complete the motor task. This information is mainly visual and is called "feed-forward", because it is "fed" into the central nervous system before the actual motion occurs. These areas project into the Motor Cortex, which actually fulfills the function of an interneuron, since it integrates sensory information and organizes parameters, such as speed, direction and the type of muscle fibers which are required for the action.

Movement alone, without a context doesn't have the same meaning for the brain!

Current evidence supports the underlying hypotheses of the N.A.P. concept, that the functional relevance of joint mobilization, demands placed upon the skeletal system and neuromuscular activation patterns depend on treatment of these structures within realistic activities in order to achieve long-term changes in synaptic connectivity and neural representation (Duchateau et al., 2006, Zehr, 2006, Adkins et al., 2006).

Voluntary action entails more than just muscle contraction.

Different neuron poulations are activated when a movement is performed without a context than when it is performed within a context. Activation of the motor cortex alone, leads to a caricature of a movement as opposed to an activity within an environmental context (fig. 3a, 3b, 3c). Body representations within the cortex are also not limited to just representing a specific part of the body, but show functional connections (fig. 4) (Graziano, 2002).

Clinical example

A right-handed 16 year - old patient, E. L., experienced spontaneous pain in her left wrist and was diagnosed by her medical doctor with acute tendinitis. Immobilization in a cast was prescribed. After 5 days she complained about excruciating pain and the cast was removed. Her entire arm was extremely painful and absolutely no voluntary action of her wrist and finger extensor was possible, although nerve conduction tests proved normal. After 2 months she was able to achieve a voluntary contraction of these muscles, although her activation pattern was quite abnormal, since only mass movements were possible. The clinical picture of spastic dystonia prevailed (fig. 3a). On the same day, she was asked to bounce a gym ball and to return overhead volleys with a volley ball (fig. 3b). These movements were totally

Fig. 3a. The patient shows spastic dystonia, when trying to extend her skillful movement, within the context

Fig. 3b. She shows coordinated, wrist and fingers. of throwing a ball.

Fig. 3c. Even when playing a flute she is able to perform selective finger extension.

normal in the video documentation, as were her selective finger movements when playing a flute(fig. 3c).

B. Muscular Plasticity

According to functional demands, muscle mass, in general, increases or decreases. Although strength training induces muscle hypertrophy, it cannot be concluded that this trained muscle will automatically be able to perform different activities skillfully. Each activity requires a specific recruitment order within the muscle itself (intramuscular coordination) and a specific timing among the muscles within the synergy, performing the action (intermuscular coordination). Also the frequency of muscle fiber recruitment is determined by the task itself. Muscle strengthening, therefore, requires training in

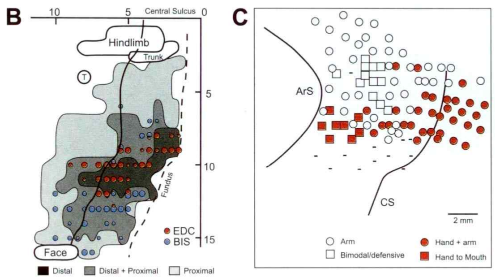

Fig. 4. Hand and arm activation patterns, following intracortical stimulation of the primary motor cortex and pre-motor areas of wake monkeys.

variable conditions, in order to attain the coordination needed for different tasks.

Certain pathologies cause changes in the type of muscle fibers. It has been found that in spasticity, for example, phasic (fast-twitch) fibers change into tonic (slow twitch) fibers (Hufschmidt, Mauritz, 1985). This is also the case during increase of age, where a gradual change from phasic fibers into tonic fibers occurs.

Structural adaptability

Muscles must be capable to change their length according to the demands of the activity and the environment. Postural adjustments require eccentric control of extensor synergies. For this, structural elasticity is required.

If immobilization is necessary for wound healing, stiffness may occur. Muscle stiffness is defined by the force required to change the length of a resting muscle (Dietz and Berger, 1983).

Changes in tendon and connective tissues, such as water loss and collagen deposition, are presumed to cause stiffness (Van den Berg, 2000).

Muscle stiffness may also be the result of protective strategies. One just has to imagine walking on ice. A very efficient strategy to gain motor control in this situation is co-contraction. Momentary stiffness is not only required to gain stability but also a very natural consequence to fear of falling. If co-contraction persists then structural stiffness results.

Interestingly, experiments have shown that training can indeed change the type of muscle fibers within muscles. Sprinters, for example, have a predominantly high number of phasic muscle fibers. During a period of resistance-training, though, the amount of fast twitch fibers diminish. Two months after conclusion

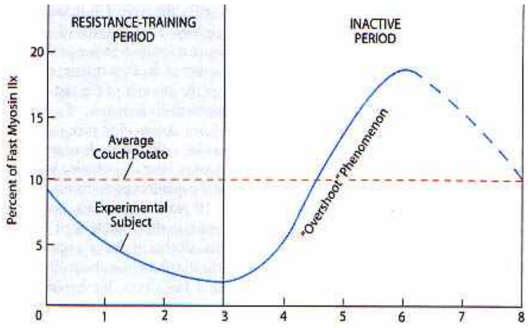

Fig. 5. 3 months after strength training, the number of phasic muscle fibers diminish. After further 2 months, a so-called overshoot phenomena occurs.

of resistance-training, the same amount of fast-twitch fibers are attained as before the training period. Astonishingly, after 3 months, double the amount of fast-twitch fibers were discovered (Andersen, Schjerling, Saltin, 2000) (Fig.5). This shows that training causes changes, not only in the muscle mass itself, but also of the specific fiber type.

C. Arthro-osar (Skeletal) Plasticity

Since muscle activation is required to move and stabilize joints, changes in muscle activation patterns will cause changes in the skeletal system. For example, if the hip extensor synergy is not strong enough to stabilize the ileum on the femur head, then the ileum will tilt forward and the load to the femur head will increase. Osteophytes are produced as a protective mechanism. If pressure to bone mass is decreased, then adaption also occurs. Astronauts lose bone mass after a period of time in space, because their bones are not exposed to gravity. Functional demands determine the structure. Even throughout evolution one can observe this principle. Throughout time, the form of our skull has changed, according to functional demands. The area where speech is organized (Broca Center) grew larger when homo sapiens began to speak. This area also controls finger, tongue and face muscles, as well as the hearing of sounds, all of which are attributes involved in communication.

Ⅱ. Task Specific Organization of Postural Control and Reciprocal Innervation

Postural control may be defined as the ability to maintain the center of body mass over the base of support, under both static and dynamic conditions. It includes organizing multiple sensory strategies for orientation. An important feature of postural synergies, which distinguishes them from abnormal synergies, is their ability to be modified.

Sherrington regarded reciprocal inhibition as a general method for coordinating priorities, which enables the unique character of goal-oriented behavior (Kandel, 2006). As discussed above, executing a voluntary movement requires a specific recruitment order of the agonist (intermuscular coordination) and of the muscle fiber types within the muscles (intramuscular coordination), as well as a specific recruitment frequency (Schmidtbleicher, Gollhofer, 1991). Depending on the task, the antagonist may have to relax or may have to maintain coactivity (co-contraction). Different environmental conditions also require variable reciprocal innervation. Gravity conditions, for example, determine if the antagonists have to control the movement eccentrically.

Feedforward and Feedback

As discussed before, at the beginning of voluntary goal-oriented movements information is "fed" into the central nervous system. This information is used to plan and initiate the movement. Towards the end of the movement, feedback-mechanisms become more important, so that corrections can be made, if necessary (Mulder, 2006). Different tasks require and use different information. Quick movements rely more on feed-forward mechanisms. There is no time for feedback. Sensory feedback is necessary, however, to create the brain's model of the movement in the first place and this process contributes to the acquisition of new motor skills(Rosenbaum, 1991). Feedback is also needed for making corrections, especially if unpredictable changes occur, during the execution of a movement.

Fast goal-oriented voluntary actions require a so-called *"tri-phasic activation pattern"* (Beradelli et. al., 1996, Ghez, Thach, 2000). First the agonist fire to accelerate the movement. Shortly before arriving the goal, the antagonists contract to decelerate, after which the antagonists fire a second time to stabilize the end position. During the acceleration phase, the antagonists need to be reciprocally inhibited. They receive this information via interneuron connections. One can say, that when an agonist contracts, the antagonist must "know" what to do. When catching a ball, for example, not only the biceps must react to the stretch stimulus caused by the weight of the ball, but the triceps must also contract for stability. This co-contraction is organized even *before* the ball actually reaches the hand, in anticpation that something instable is going to happen (Ghez, Thach, 2000). This depends primarily on visual information (feedforward). The impact of the ball provides proprioceptive information so that the biceps can react (feedback). Anticipation of the destabilization, causes the triceps to contract as well. An apple of the same weight held in the hand, which someone wants to bite into, won´t cause the triceps to co-contract. For this task, it needs to be inhibited.

Ⅲ. Protective Mechanisms

The underlying hypothesis for the treatment methods within the N.A.P. concept is, that during a goal-oriented voluntary movement, when antagonists should normally relax, they may instead co-activate, in order to avoid movements which have been painful or still are. In this way, the need for protection could be fulfilled. If protection of a body part is necessary for healing to occur, then the muscles will try to "freeze" the painful and injured body parts. The same strategy is organized when stability is required, for example, falling may be a risk. Especially when walking on an unstable or slippery surface, this strategy may be required.

Scientific evidence has shown that protective strategies are triggered by the amygdala of the limbic system and that these are organized subconsciously (Le Doux, 1999). The fact that muscles need to alter their activity according to changing demands and, that reciprocal innervation is organized variability, as illustrated above, supports this treatment hypothesis.

The amygdala, a structure of the limbic system, is directly connected to the sympathetic nervous system, which in turn, triggers bio-chemical changes. The aim of this mechanism is to keep painful body parts from moving, so that healing may occur.

If harmful stimuli continue, hypersensitivity within the entire nervous system may result (Butler, 2000). Serotonin is an important transmitter for long-term memory, which explains why all these changes may be "learned." (Le Doux, 1999, Squire and Kandel, 1999). These protective mechanisms entail physiological changes, which are necessary in the acute phase of wound healing. To prevent these changes from become chronic, It is very important to make positive movement experiences with the injured body part as soon as possible!

A. Inhibition and Habituation

Habituation may be seen as a behavioral reaction to repeated stimuli, which are uncomfortable, but cause no harm. It entails progressive decrease in response to repetion of a stimulus. The process of habituation is not conscious. Without it, one wouldn´t be able to shift attention when background information seems more important, although the same stimuli continue. As soon as these seem unimportant, one is able to focus attention to the, seemingly, more important matter. For this, neural adaptation is necessary.

Habituation depends on Inhibition.

Inhibitory neurons trigger a stable, predictable and coordinated reaction to a specific stimulus, by inhibiting all competing reflexes, except one. A single motor-neuron adds up all facilitatory and inhibitatory impulses which it receives from other neurons. On the basis of this calculation, an appropriate action occurs (Kandel, 2006).

Ⅳ. Hands-Off and Hands-On for improving Motor Control

Voluntary goal-oriented actions are organized both cortically and subcortically (Ghez, Krakauer, 2000). It was long believed that sensory input is required for movement initiation. Experiments have shown, that movement initiation requires cognitive information, pertaining to the environment, such as visual and auditory input. Tactile sensory information is used for feedback, to control if the desired action plan has occurred and if corrections are necessary (Mulder, 2006). The result of this evidence is that tactile information can be used to gain coordination of skillful movements *during* the execution of a specific task. Perception requires searching the appropriate information, which is relevant for the task and the most beneficial strategies to accomplish the goal. Feeling, alone, does not enable the brain to organize movements. The feeling of what is happening is what counts. This is not dependent on consciousness.

Distal body parts are organized primarily consciously (cortically) and require visual information from the environment. Proximal body parts are organized primarily subconsciously (subcortically) and require proprioceptive information.

Within the N.A.P. concept, goals are directed by use of visual and verbal information. The therapist´s hands are used as a tool to establish the biomechanical situation, which the muscles are not able to coordinate automatically. In doing so, the brain is able to organize the appropriate muscle synergies, which may be recruited automatically as motor learning progresses.

Therapy Goals

Therapy goals within the N.A.P. concept are to:

1. Prevent pain awareness and fear during the acute phase.
2. Enhance resources and/or coping strategies, for independent activities.
3. Increase elasticity, prevent or treat stiffness and/or contracture.
4. Facilitate cortical representation of weak bodyparts, taking the proper biomechanical requirements into consideration and avoiding unnecessary compensation strategies.
5. Facilitate individual needs and professional activities, within elevant environmental contexts.

Methods include following characteristics:

1. The patient is guided to organize the activity.
   - His attention is focused towards input systems needed for the specific task.
   - For patients with cognitive deficits, the therapist needs to choose contexts, in which relevant activities can be practiced.
2. Combining "being handled" and "handling the action" influences structures within the goal-oriented activity, itself.
   - The therapist's hands are used to organize the biomechanical situation, required for economic and safe strategies.
   - The therapist's hand are applied after he/she has assured him-/herself that the goal is clear to the patient.
3. Positions are chosen specifically.
   - Mainly positions are chosen in which the patient is able to perform his daily life activities and participate in socio-cultural activities.
   - The influence of gravity is considered, depending on the necessary muscle activation and the structure being treated.

Case report

A 36 year - old dentist survived a severe motor vehicle accident with a plexus brachiales paresis lesion of his right, dominant arm, among other severe injuries. Due to several weeks of bed rest, his shoulder became stiff. Especially the loss of mobility, as well as activation, in elbow flexion and supination, were fundamental for resuming his professional carrer as a dentist. The feeling in his fingers and mobility was intact.

Fig. 6.

Hypotheses:

1. Scar tissue in the surroundings of the musculocutaneous nerve has a negative effect on synaptic efficacy and leads to weakness in the biceps muscle.
2. Structural treatment must be performed within meaningful tasks.
3. The patient will only be able to learn to use his hand and arm by practicing within relevant contexts.

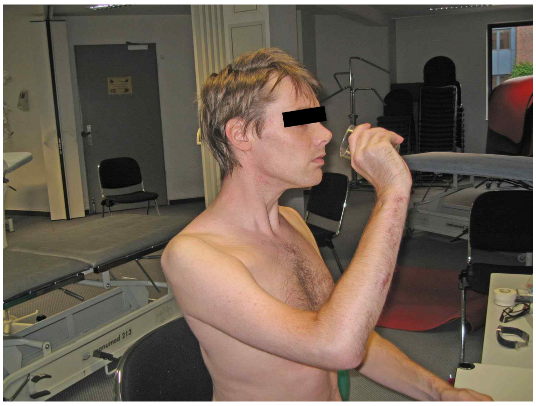

Fig. 7.

Fig. 8.

Assessment at activity level:

3 months after his accident he is not able to touch his mouth with his hand. He is able to reach his nose in side-lying. The biceps shows slight activation which is palpable. In supine he is able to flex his elbow to 80° with no supination(Fig. 6).

7 months after his accident he is able to lift a glas to his mouth two times in sitting position(Fig. 7).

8 months after his accident the same activity is possible 10 times, but still with pronation and no supination. He is also able to reach his mouth in supine(Fig. 8).

Therapy:

The patient is asked to imagine himself doing pull-ups. To increase his mobility in elbow flexion, the therapist applies traction with her distal hand, during which she glides the olecranon with her proximal hand, to increase elbow flexion(Fig. 9).

The same activity is performed in standing. The patient pulls himself forward onto his right stance leg, while trying to gras a holm. To increase mobility in supination, the therapist mobilizes the distal radio-ulnar joint

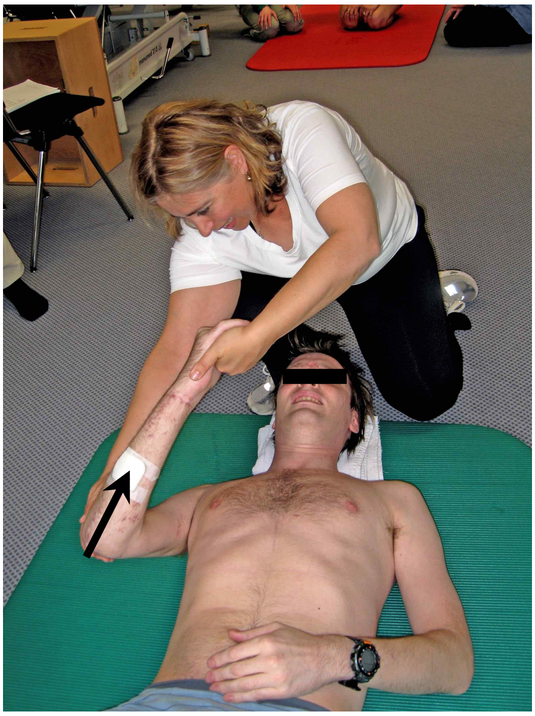

Fig. 9.

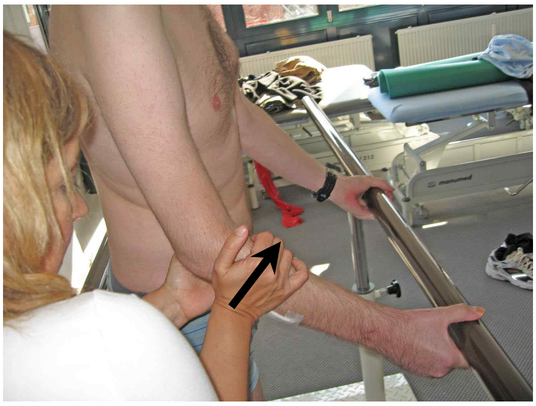

Fig. 11.

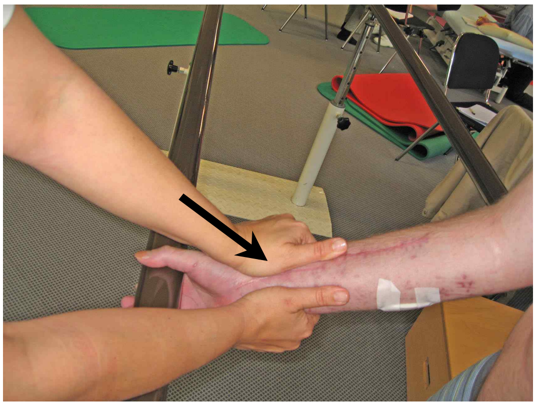

Fig. 10.

Fig. 12.

by application of pressure to the distal radius in a dorsal direction(Fig. 10).

The proximal radio-ulnar joint is also mobilized during the same activity by applying pressure to the radius head in a ventral direction(Fig. 11). 8 months after his accident he is still not able to supinate his forearm in elbow flexion (Fig. 12).9 months after his accident he is able to perform supination with elbow flexion, while trying to simulate his professional activity (Fig. 13). The therapist assists his supination activity and stabilizes his shoulder while he performs the actual task with his dental instrument (Fig. 14).

11 months after his accident the patient is able to perform quick, skillful supination movements during elbow flexion and retained full strength of his biceps muscle (Fig. 15 + 16).

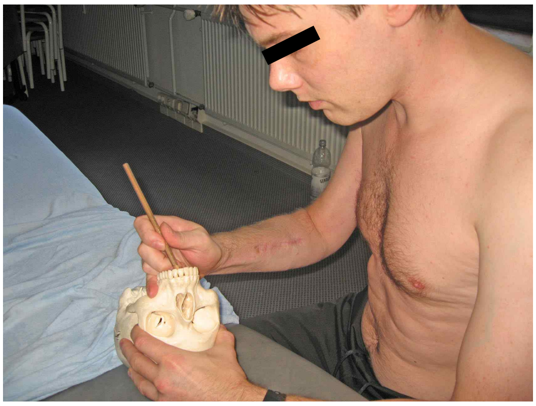

Fig. 13.

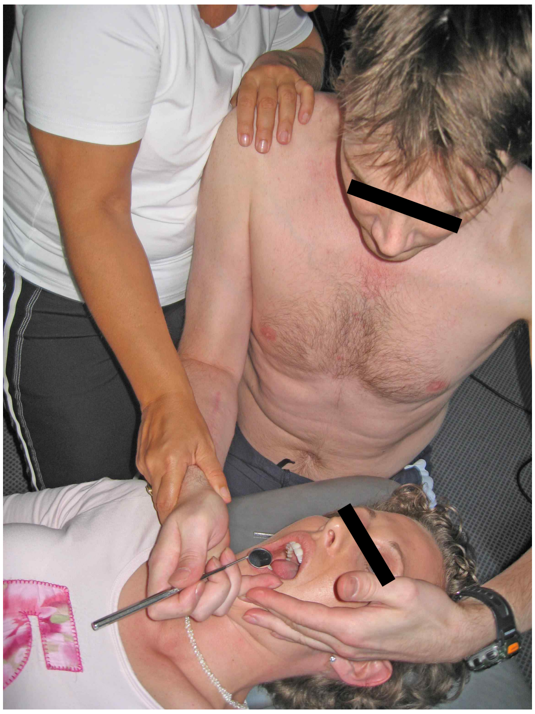

Fig. 14.

He returned to work to treat his own patients successfully in less than a year!

Conclusion

These amazing results are not only due to specific treatment methods of the N.A.P. concept, but also thanks to personal motivation of individual clients. The central goal in

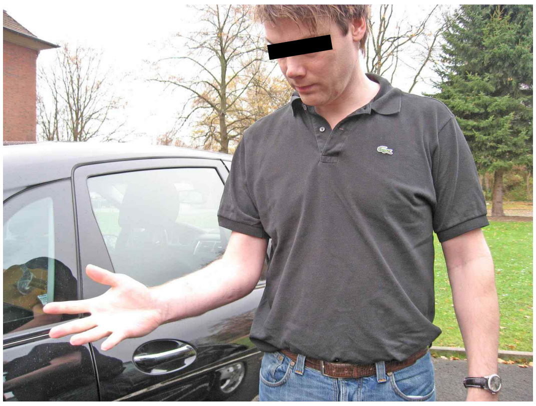

Fig. 15.

Fig. 16.

rehabilitation is to prepare the patient for his "normal" life and to encourage his social interaction(Fries, 2007). Especially at the participation level, the therapist may be able to find hidden potentials and key factors for motivation, which can enhance the rehabilitation process. Most important is, communication between the patient, his health care professionals, medical doctors, insurance companies and relatives, to determine mutual therapy goals. Single case studies undermine the importance of incorporating structural requirements within meaningful activities and during participation. The methods of the N.A.P. concept are based on current biomedical knowledge and, herewith, evidence-based. Single case reports can serve to document individual positive results. They can also lead the way to future randomized controlled trials, which are necessary to provide evidence for the efficacy of the treatment approaches within the N.A.P. concept.

Literature

Adkins DL, Boychuk J, Remple M, Kleim JA (2006). *Motor training induces experience-specific patterns of plasticity across motor cortex and spinal cord*. J Appl Physiol 101: 1776-1782.

Andersen JL, Schjerling P, Saltin B. (2000). *Muscles, Genes and Athletic Performance*. Scientific American; 283:9: pp.30-37.

Beradelli AM, Hallett JC, Rothwell R, Agostino M, Manfredi PD, Thompson CD, Marsden CD (1996). *Single-joint rapid arm movements in normal subjects and in patients with motor disorders*. Brain;119:661-664.

Berry MM, Standring SM, Bannister LH (1995). *Nervous System*. In: Bannister LH, Berry MM, Collins P, Dyson M, Dussek JE, Ferguson MWJ, eds. Gray's Anatomy, 38th ed. New York: Churchill Livingstone.

Dietz V, Berger W (1983). *Normal and impaired regulation of muscle stiffness in gait: a new hypothesis about muscle hypertonia*. Experimental Neurology. 1983;79:680-687.

Duchateau J, Semmler JG, Enoka RM (2006). *Training adaptations in the behavior of human motor units*. J Appl Physiol 101: 1776-1775.

Edelman GM (1987). *Neuronal Darwinism: The Theory of Neuronal Group Selection*. New York: Basic Books;.

Fheodoroff K, Wissel J, Entner T, Freimuller M. Measuring outcome in spasticity rehabilitation. Wien Klin Wochenschr. 2001;113; Suppl 4:11-14.

Förderreuther S (2004). *Klinische, elektro-physiologische und bildgebende Befunde bei Patienten mit komplexem regionalen Schmerzsyndrom (CRPS)*. Klinische Neurophysiologie;4:235-240.

Flor H, Elbert T, Knecht S, Wienbruch C, Pantev C, Birbaumer N, Larbig W, Taub E(1995). Phantom-limb pain as a perceptual correlate of cortical reorganization following arm amputation. Nature. Jun 8;375(6531): 482-4.

Fries W, Lössl H, Wagenhäuser S (2007). *Teilhaben!* Thieme, Stuutgart.

Ghez C, Krakauer J 2000. *The Organisation of Movement*. In: Kandel E, Schwarz JH, Jessell TM, eds. Principles of Neural Science; 656, 668. McGraw Hill, New York.

Ghez C, Thach WT (2000). *The Cerebellum*. In: Kandel E, Schwarz JH, Jessell TM, eds. Principles of Neural Science. New York: McGraw Hill.

Graziano et al. (2002), In: Riehle A, Vaadia E, eds. *Motor Cortex in Voluntary Movements*, 171, CRC Press, Boca Raton.

Hufschmidt A, Mauritz K.-H (1985). *Chronic transformation of muscle in spasticity: a peripheral contribution to increased tone*. Journal of Neurology, Neurosurgery, and Psychiatry.;48:676-685.

Iacoboni M, Molnar- Szakacs I, Gallese V, Buccino G, Mazziotta JC, Rizzolatti G(2005). *Grasping the intensions of others with one´s own mirror neuron system*. Plos Biol., March 3 (3); e79.

Kandel ER, Schwartz JH, Jessell TM (2000). *Principles of Neural Science* 4th ed. New York, St. Louis, San Francisco: Mc-Graw Hill.

Kandel ER (2006). *Auf der Suche nach dem Gedächtnis*. Siedler, München.

Le Doux J (1999). *Das Gedächtnis für Angst*. In: Spektrum der Wissenschaft Dossier. Stress, "Neurobiologie der Angst"; 3:16-23.

Leroi-Gourhan A. Hand und Wort. Frankfurt: Suhrkamp; 1995.

Maihöfner C, Handwerker HO, Neundörfer B, Birklein F (2003). Patterns of cortical *reorganization in complex regional pain syndrome*. Neurology. Dec 23;61(12):1707-15.

Merzenich MM, Nelson RJ, Stryker MP, Shoppmann A, Zook JM (1984). *Somato-sensory cortical map changes following digital amputation in adult monkey*. Journal comp. Neurologys;224:591-605.

Mulder T (2006): *Das adaptive Gehirn*. Thieme, Stuttgart; pp.54-57.

Ojemann. In: Calvin WH. Wie das Gehirn denkt. München: Elsevier; 1994.

Pasqual-Leone A, Torres F(1993). *Plasticity of the sensorimotor cortex representation of the reading finger in Braille readers*. Brain.;116:39-52.

Pearson K, Gordon J (2000). *Spinal Reflexes*. In: Kandel ER, Jessell JH, Schwartz TM, eds. Principles of Neural Science; 714, 722. New York: McGraw-Hill.

Ramachandran VS (1993). *Behavioral and magnetoencephalographic correlates of plasticity in the adult human brain*. Proc Natl Acad Sci. USA.;90:10413-10420.

Rosenbaum DA (1991). *Human Motor Control*. San Diego, CA: Academic Press;.

Schmidtbleicher D, Gollhofer A(1991). *Specific methods of strength training also in rehabilitation*. Sportverletz Sportschaden. sep, 5(3): 135-41.

Schmidt R. Motor Control and learning: a behavioural emphasis. Champaign, Ill.: Human Kinetics; 1999.

Sherrington C. (1947). The Integrative Action of the Nervous System. Cambridge: Cambridge University Press.

Squire LR, Kandel ER (1999). *Gedächtnis. Die Natur des Erinnerns*. Heidelberg: Spektrum.

Tabary JC, Tabary C, Tardieu G et al. (1972). *Physiological and structural changes in the cat soleus muscle due to immobilisation at different lengths by plaster casts*. Journal of Physiology; 224:231-244.

Taub E. (1980). *Somatosensory deafferation in research with monkeys: implications for rehabilitation medicine*. In: Behavioural Psychology and rehabilitation Medicine 8ed. LP Ince. Baltimore MD: Williams and Wilkins; 371-401.

Van den Berg F (2000). *Angewandte Physiologie für Physiotherapeuten*, Bd. 1.-3. Thieme, Stuttgart.

Williams PE, Goldspink G (1978). *Changes in sarkomer length and physical properties in immobilized muscle*. Journal of Anatomy; 127:459-468.

Witzmann FA, Kim DH, Fitts RH (1982). *Hindlimb immobilisation: length-tension and contractile properties of skeletal muscle*. Journal of Applied Physiology; 53: pp.335-345.

Zanette G, Tinazzi M, Bonato C, di Summa A, Manganotti P, Polo A, Fiaschi A (1997). *Reversible changes of motor cortical outputs following immobilization of the upper limb*. Electroencephalogr Clin Neurophysiol. Aug; 105(4):269-79.

Zehr EP (2006). *Training-induced adaptive plasticity in human somatosensory reflex pathways*. J Appl Physiol 101:1783-1794.