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Perspective

A Modern Neuroscience Approach to Chronic Spinal Pain: Combining Pain Neuroscience Education With Cognition-Targeted Motor Control Training

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Abstract

Chronic spinal pain (CSP) is a severely disabling disorder, including non-traumatic chronic low back and neck pain, failed back surgery and chronic whiplash associated disorders. Much of the current therapy is focused on input mechanisms (treating peripheral elements like muscles and joints) and output mechanisms (addressing motor control), while there is less attention to processing (central) mechanisms. In addition to the compelling evidence for impaired motor control of spinal muscles in patients with CSP, there is increasing evidence that central mechanisms, i.e. hyperexcitability of the central nervous system and brain abnormalities play a role in CSP. Hence, treatments for CSP should not only address peripheral dysfunctions, but also the brain. Therefore, a modern neuroscience approach, comprising of therapeutic pain neuroscience education followed by cognition-targeted motor control training, is proposed. This perspective paper explains why and how such an approach to CSP can be applied in physical therapy practice.
Chronic spinal pain (CSP) includes non-recurrent chronic low back pain, failed back surgery, chronic whiplash associated disorders, chronic non-traumatic neck pain, among others, and accounts for a large proportion of the chronic pain population\(^1\). CSP is a severely disabling disorder characterized by tremendous personal and socioeconomic impact, with long-term sick-leave, low quality of life and very high socio-economical costs\(^2\).

Within the context of the management of painful musculoskeletal disorders, it is crucial to consider the concept of pain mechanisms\(^3\). Pain mechanisms have been broadly categorized into: 1) input mechanisms, including nociceptive pain and peripheral neurogenic pain 2) processing mechanisms, including central pain and central sensitization, and the cognitive-affective mechanisms of pain and 3) output mechanisms, including autonomic, motor, neuroendocrine and immune system\(^4\). Except for inflammatory pain conditions (for example rheumatoid arthritis) or non-inflammatory sources of ongoing spinal nociception, the stage of real tissue damage or nociception has disappeared in CSP. Within this context there is increasing evidence that central mechanisms, i.e. brain abnormalities (changes in brain structure and function) and hyperexcitability of the central nervous system (sensitization of the brain) play a tremendous role in CSP patients.

Brain atrophy, especially decrease in the density of brain grey matter (containing the neural cell bodies)\(^5\)-\(^10\), has been shown repeatedly in patients with chronic low back pain. Besides brain atrophy, descending pain inhibition or brain-orchestrated analgesia is malfunctioning in people with CSP\(^11\)-\(^14\). The latter suggests a cardinal role for hyperexcitability of the central nervous system, or central sensitization, in patients with CSP. Many patients with CSP show features of central sensitization\(^2\),\(^11\),\(^13\)-\(^22\), which is operationally defined as “an amplification of neural signalling within the central nervous system that elicits pain hypersensitivity”\(^23\).
In addition to the disturbed pain and central brain mechanisms, there is compelling evidence for impaired motor control in patients with CSP. Intriguingly, these dysfunctions do not spontaneously resolve when spinal pain dissipates and our previous accomplishments have shown that these dysfunctions are even observable in recurrent patients during periods of remission. Optimal function of the back muscles is a prerequisite for static and dynamic control of spinal stiffness and movement. This implies that spinal muscles of patients with CSP are no longer able to accurately control body postures and movements.

Much of our current therapy is focused on input mechanisms (treating peripheral elements like muscles and joints) and output mechanisms (addressing motor control), while there is less attention to processing (central) mechanisms. Although randomized clinical trials have shown that exercise therapy for improving spinal motor control is effective in reducing pain and disability related to CSP, the effects are similar to those seen in response to general exercise therapy not addressing spinal motor control. In addition, the effect sizes of exercise therapy for improving spinal motor control in CSP patients are rather small, limiting its socioeconomic impact.

In order to adopt the treatment for the brain abnormalities seen in patients with CSP, and increase the effect sizes and socioeconomic impact of treatment for CSP, it seems to be mandatory to address the central mechanisms in CSP as well. This asks for a modern neuroscience approach to CSP using a comprehensive rehabilitation program comprising of pain neuroscience education followed by cognition-targeted motor control training. At present, physical therapy for patients with CSP is either based on a pure biomedical model (e.g. neuromuscular training), or is biopsychosocially driven (e.g. graded exposure in vivo,
graded activity, multidisciplinary pain treatment). This perspective paper argues to combine both approaches in an approach, that addresses peripheral dysfunctions (here narrowed to impaired motor control of spinal muscles) in a broader biopsychosocially-driven framework.

In the first part of the paper, the theoretical rationale for applying the modern neuroscience approach to CSP is presented. In the second part, the application in clinical practice is explained.

Abnormal Brain Structure and Function in Patients With Chronic Spinal Pain

The interplay between the brain and the spinal muscles is crucial for accurate control of body movements and postures, suggesting that in patients with CSP the function and structure of the brain may even so be affected. This reasoning has been confirmed by several neuroscience studies. Brain atrophy, especially brain grey matter density and volume decrease\textsuperscript{5-10}, has been shown repeatedly in patients with chronic low back pain. These studies demonstrated a loss of grey matter volume in patients with chronic low back pain compared to healthy controls, more specifically in the dorsolateral prefrontal cortex, thalamus, brainstem and somatosensory cortex, which was strongly correlated with pain duration and pain intensity. Yet studies examining the brain grey matter density and volume in patients with acute (spinal) pain are essentially lacking. Such studies, including longitudinal studies examining the transition from acute to chronic spinal pain, are required for assessing the true meaning of the observed changes in brain grey matter density and volume in patients with chronic spinal pain.

Longitudinal studies should unravel whether brain changes are the cause or the consequence of pain.
One study examined the transition from subacute to chronic low back pain, and found that when pain persisted (in contrast to recovering low back pain patients and healthy controls), brain gray matter density decreased\textsuperscript{40}. Recent studies, investigating the effect of surgical interventions, demonstrated that many of the grey matter changes observed in pain patients subsided with cessation of pain\textsuperscript{41-43}. It is therefore suggested that the grey matter abnormalities found in CSP do not reflect brain damage but rather a reversible consequence of chronic pain, which normalizes when the pain is adequately treated. However, until now, no brain imaging studies have evaluated how physical therapy can influence grey matter volume.

Brain atrophy is not the only brain abnormality observed in patients with CSP. Impaired motor control of spinal muscles in recurrent and CSP implies maladaptive brain plasticity of motor control-related brain areas\textsuperscript{24,44-46}. In other words: in patients with CSP, the brain regions involved in spinal motor control are altered, which influences the brain’s capacity to accurately control body movements and postures. Hence, the brain of patients with CSP appears to undergo changes not only with regard to structure, but also in function, especially of regions involved in spinal motor control. This is often referred to as reorganization of motor control-related brain areas or smudging of the motor brain\textsuperscript{24,44-46}. No wonder patients with CSP have difficulty in fine-tuning body movements during daily living activities.

Interestingly, the brain abnormalities in patients with CSP are reversible: one uncontrolled study showed that effective medical pain treatment (surgery or infiltrations) is accompanied by restoration of brain atrophy (grey matter volume) and function (brain activity during cognitive tasks) in humans with chronic low back pain\textsuperscript{5}, but further studies are required to confirm these preliminary findings to other treatments with known long-term benefits like exercise and behavioural therapies. In another study it was shown that motor control training,
and not unskilled general exercise, can reverse reorganisation of the motor cortex in patients with CSP (i.e. low back pain)\textsuperscript{47}. The observed relationship between cortical reorganisation and changes in motor coordination following motor training stresses the potential mechanisms of this specific approach.

The Sensitized Brain of Patients With Chronic Spinal Pain

With respect to the altered brain function, not only motor-control related brain areas are involved, but also brain-orchestrated pain processing is malfunctioning in people with CSP\textsuperscript{11-14}. Briefly, the brain controls two major pain systems: a facilitatory (the accelerator) and inhibitory (the brake) system. Malfunctioning of brain-orchestrated analgesia in CSP implies that the brake is not working properly, contributing to the process of central sensitization, which is thought to play an important role in different chronic pain populations.

Central sensitization, characterized by generalized hypersensitivity of the somatosensory system\textsuperscript{48}, is due to a dominance of the facilitatory over the inhibitory system. More specifically at the brain level, central sensitization encompasses altered sensory processing\textsuperscript{49}, malfunctioning descending inhibition\textsuperscript{50}, increased activity of descending pain facilitatory pathways, and an increased efficacy in processing of incoming nociceptive stimuli (temporal summation of second pain or wind-up\textsuperscript{49}, and long-term potentiation\textsuperscript{51,52}). In addition, the brain regions and circuits activated during pain (i.e. the pain neuromatrix) differ: patients with central sensitization and CSP show more brain activity in response to painful stimuli, and have brain activity in regions normally not involved in pain sensations\textsuperscript{53}. It is important to highlight that central sensitization is not only seen in chronic pain patients, but has been demonstrated to occur soon after injury\textsuperscript{17} and is dependent upon the context of the injury (environmental influences surrounding the injurious event).
A brain that is constantly processing a pain experience does not have the opportunity to maintain circuitry for fine motor control, postural control, language, and even emotions. These changes are observed as maladaptive ‘output mechanisms’ in these patients whereby they become incapable of isolating a particular muscle in a motor control exercise. Within this respect it is important to highlight the impact of unhelpful emotions such as emotional distress and the neurobiological evidence suggesting they generate central nervous system pain sensitization.

Clinically, central sensitization implies that patients show decreased pain thresholds all over their body, as well as increased sensitivity for non-mechanical stimuli like bright light, sound/noise, stress, odours, and medication. Patients typically experience disproportionate pain, implying that the severity of pain and related disability (e.g. intolerance to daily life activities) are disproportionate to the nature and extent of injury or pathology (i.e. tissue damage).

Many patients with chronic (spinal) pain, including those with chronic (traumatic) neck pain, chronic pelvic pain, chronic low back pain, osteoarthritis, and rheumatoid arthritis show features of central sensitization. Our group has contributed to this understanding, including several studies in patients with CSP. The studies that provided evidence favouring central sensitization in patients with CSP mainly include brain imaging studies, psychophysical testing, and cerebral metabolism studies. Given the increased awareness that central sensitization provides an evidence-based explanation for many cases of CSP, rehabilitation of such patients should target, or at least take into account the process of central sensitization.
A Modern Neuroscience Approach for the Treatment of Chronic Spinal Pain

As studies have demonstrated that CSP patients demonstrate both changes in peripheral dysfunctions as well as alterations in brain structure and function, treatments for CSP should not only address the peripheral dysfunctions of spinal muscles and joints, but also the brain. Therefore, it is our belief that an accurate approach has to tackle both, which means that pain neuroscience education is followed by a more specific treatment of the movement dysfunction. The second part can consist of different treatment components accounting for our current understanding of spinal pain (e.g. hands-on manual therapy, graded activity, exercise therapy with different therapeutic goals; circulation/sensorimotor control/mobility/endurance/strength/...), depending of what emerges from the clinical reasoning as the most dominant peripheral dysfunction. This paper intends to focus on motor control dysfunctions as a dominant peripheral dysfunction in CSP and puts forward the “modern neuroscience approach”.

This approach to CSP entails pain neuroscience education followed by cognition-targeted motor control training. For clarity reasons the treatment is divided into 3 consecutive phases. However, in clinical practice the 3 phases will naturally merge together.

**Phase 1: Therapeutic Pain Neuroscience Education**

The presence of central sensitization implies that the brain produces pain, fatigue and other ‘warning signs’ even when there is no real tissue damage or nociception. This can be addressed by explaining to CSP patients the mechanism of central sensitization with evidence from modern neuroscience, a strategy known as therapeutic pain neuroscience education.
Therapeutic pain neuroscience education enables CSP patients to understand the controversy surrounding their pain, including the lack of objective biomarkers or imaging findings. One of the main goals of therapeutic pain neuroscience education is changing pain beliefs through the reconceptualization of pain. The focus is convincing patients that pain does not per se result from tissue damage. Pain neuroscience has taught us that pain is often present without tissue damage, is often disproportionate to tissue damage, and that tissue damage (and nociception) does not per se result in the feeling of pain. To some extent, this relates to the clinical feature of “hurting versus harming”, for which there is much scientific support, for instance with the fear avoidance model\textsuperscript{60-62} that can be placed in a multidimensional framework\textsuperscript{63}. Therapeutic pain neuroscience education intends to transfer this knowledge to CSP patients. This enables applying a time-contingent (“Perform the exercise for five minutes, regardless of the pain”) instead of a symptom-contingent (“Stop the exercise once it hurts”) approach to exercises and physical activity.

Why preferring a time-contingent approach over a symptom-contingent approach? Central sensitization implies that the brain can produce pain and other ‘warning signs’ even when there is no real tissue damage. A symptom-contingent approach may facilitate the brain in its production of nonspecific warning signs like pain, while a time-contingent approach may deactivate brain-orchestrated top-down pain facilitatory pathways. This view is supported by findings of reduced central nervous system hyperexcitability\textsuperscript{64}, and an increase in prefrontal cortical volume\textsuperscript{65} in response to time-contingent therapy in chronic pain patients.

Therapeutic pain neuroscience education is acceptable to patients\textsuperscript{66, 67}, and was found effective for changing pain beliefs and improving health status in patients with various
chronic pain disorders\textsuperscript{66, 67}, including those with CSP\textsuperscript{68-73}. However, the effects are small and education is insufficient as a sole treatment\textsuperscript{67}.

Practice guidelines for therapeutic pain neuroscience education were presented previously \textsuperscript{66, 67}; it encompasses 2 to 3 individual sessions spread over at least 2 weeks. Detailed pain neuroscience education is required to reconceptualise pain, and to convince the patient that hypersensitivity of the central nervous system rather than local tissue damage may be the cause of their presenting symptoms. The content of the education sessions can be based on the book “Explain Pain” \textsuperscript{74}, covering the characteristics of acute versus chronic pain, the purpose of acute pain, how acute pain originates in the nervous system (nociceptors, ion gates, neurons, action potential, nociception, peripheral sensitization, synapses, synaptic gap, inhibitory/excitatory chemicals, spinal cord, descending/ascending pain pathways, role of the brain, pain memory and pain perception), and how pain becomes chronic (plasticity of the nervous system, modulation, modification, central sensitization, the pain neuromatrix theory).

One of the common pitfalls of this approach implies the patient’s misunderstanding the neuroscience education message and believing that they are being told “the pain is all in your head.” This can be prevented by in-depth explanation of the neurophysiology of pain and chronic pain, before discussing the potential sustaining factors of central sensitization like emotions, stress, illness perceptions, pain cognitions and pain behaviour. Acute nociceptive mechanisms are typically explained first and are then contrasted with central sensitization processes i.e. in the case of chronic spinal pain. Illustrations, examples, and metaphors are frequently used \textsuperscript{75}. This can become a challenge, particularly to patients of modest intellectual capability or those distracted by strong emotion. Therefore, the general messages need to be
delivered in a language and at a pace that takes into account the patient’s level of intellectual ability and health literacy.

Hence, it is clear that the boundary between education and therapeutic intervention is hard to define precisely. Much more than an educational framework is required for providing effective therapeutic pain neuroscience education. The wording therapeutic pain neuroscience communication is applicable here, and such communication can open the avenue for a behavioral change (including compliance with exercise therapy). Therapeutic pain neuroscience communication should be regarded as an inherent part of the treatment program.

Therapeutic pain neuroscience education prepares patients for a time-contingent, cognition-targeted approach to daily (physical) activity and exercise therapy. Therapeutic pain neuroscience education is a continuous process initiated during educational sessions prior to and continuing into active treatment and followed-up during the longer term rehabilitation program\textsuperscript{67}, through specific exercise therapy. Before moving on to the next phase, it is often helpful to determine whether the patient has adopted adaptive pain beliefs. This can be done by thorough questioning the patient’s illness perceptions, use of self-reported measures like the Pain Catastrophizing Scale\textsuperscript{76}, or by asking the patient to explain the nature of their pain.

Once the patient has adopted adaptive beliefs regarding CSP, the next step can be taken: exercise therapy with specific emphasis on spinal motor control training. In the treatment of CSP, it is crucial not to initiate motor control training before the patient has adopted adaptive pain beliefs. Thus, therapeutic pain neuroscience education precedes motor control training\textsuperscript{71} (Figure).
The cognition-targeted motor control exercise program is divided into 2 stages (i.e. phases 2 and 3). The exercises can be introduced using motor imagery, and integrated with increasing complexity using a time-contingent progression and practiced in different environments and contexts in order to maximize transfer to daily situations. This is detailed below.

**Phase 2: Cognition-Targeted Neuromuscular Training**

The training consists of a proprioceptive, coordination and sensorimotor control training program based on the principles and ideas published in the work of many innovative researchers and clinicians like Richardson et al., Comerford et al., and Sahrmann. The exercises are designed to improve function of specific muscles of the spinal region and control of posture and movement. The aim of this phase is to restore an optimal balance between the different muscles, which often means that the deeper muscles need to be facilitated by independent activation while overactive superficial muscles need to be inhibited in an individualized manner. In patients with low back pain, this phase of the exercise program involves retraining of the deep muscles surrounding the lumbopelvic region (e.g. multifidus, transversus abdominis, psoas, pelvic floor muscles), whereas retraining of the deep cervical flexors/extensors and scapular muscles are proposed for neck pain patients.

However, within a modern neuroscience approach to CSP it is mandatory that motor control training is *cognition-targeted*. This includes the following modifications to the original motor control training program:

- all exercises are performed in a time-contingent rather than a symptom-contingent way;
- progression to a next level of (more difficult) exercises can be preceded by an intermediate phase of motor imagery (i.e. the patients are imagining that they are
performing the exercise of activity) for (re)training the brain circuitry responsible for successful execution of the targeted movement;

- the treating physical therapist is advised to address patients’ cognitions about their problems during the cognition-targeted motor control training, so that patients will have positive perceptions regarding their illness and treatment outcome;

- the latter accounts for patients’ perceptions about the outcome of the exercises as well: therapists are advised to take the time required to discuss the patient’s perceptions about each exercise. This include discussion of the anticipated consequences of the exercises (e.g. pain increase, further damage to the spine), and challenging the patient’s cognitions in relation to the exercises. The pre-exercise communication facilitates the application of the principles learned during the preparatory phase of therapeutic pain neuroscience education during exercise interventions.

**Phase 3: Cognition-Targeted Dynamic and Functional Exercises**

The purpose of this phase is to implement precision of the desired coordination, train these skills in static tasks, and incorporate them into dynamic tasks and functional positions. It involves increasing the complexity of the exercises by progressing through a range of functional tasks and exercises targeting coordination of trunk and limb movements, maintenance of optimal trunk stability, and improvement of posture and movement patterns.

Progression of exercises is targeted and developed towards those movements and/or activities for which the patient is fearful (e.g. forward bending in case of low back pain). Indeed, especially those movements and/or activities which are fearful should be exercised, meaning that the exercise program is individually-tailored. The Photograph Series of Daily Activities (PHODA) Scale can be used to obtain a hierarchy in fearful movements/activities. In
addition to the PHODA, other practical tools like the the Fear of Daily Activities Questionnaire are available for assessing specific fear of activities. The Fear of Daily Activities Questionnaire generates reliable data and appears responsive to therapeutic change. Final progression can include exercising during physically demanding tasks, but also exposure to the feared movements or activities, and exercising during cognitively and psychosocially stressful conditions. In addition, the participants should be instructed to perform a daily set of home exercises.

During the exercise program, the therapist may remind the principles learned during the therapeutic pain neuroscience education, as it is known that CSP patients who are fear avoidant show larger correlations between pain expectancies for movements depicted in the PHODA and their ratings of predicted and experienced pain during exercises. As is the case during phase 2, progression to a next level of exercises can be preceded by mentally imaging the task (motor imagery) in order to train the brain. Importantly, late-stage progression involves not only exercising during physically demanding tasks, but also exposure to the feared movements or activities, and exercises during cognitively and psychosocially stressful conditions. In such cases, therapists should try to decrease the anticipated danger (threat level) of the exercises by challenging the nature of, and reasoning behind their fears, assuring the safety of the exercises, and increasing confidence in a successful accomplishment of the exercise.

Clinical trials have shown that both pain neuroscience education and exercise therapy for improving spinal motor control are effective sole treatments for people with CSP, but small-scale studies that combined both suggest a strong synergistic effect. These studies reported large effect sizes and small numbers needed to treat. Still, the proof of concept
requires confirmation in a larger, multi-centre trial with appropriate evidence-based control intervention. Evidence of its specific clinical efficacy in comparison with cognitive and behavioral approaches for CSP is currently lacking and requires further study as well.

**Selecting Patients for the Modern Neuroscience Approach**

It needs to be considered that not all patients with CSP require motor control training. Depending of what emerges from the clinical reasoning as the most dominant peripheral dysfunction, therapeutic approaches will be chosen. Some may benefit more from grading daily physical activity levels or using aerobic exercise therapy. It is relevant to mention that in such patients the same principles as explained here can be applied: therapeutic pain neuroscience education preceding cognition-targeted grading of daily physical activity levels (i.e. graded activity) or aerobic exercise therapy (i.e. graded exercise therapy). In addition, some patients still hold catastrophic beliefs about pain and movement, including irrational fear of movement, even after intensive pain neuroscience education. This represents a pitfall as it will be inappropriate to progress with these patients towards the phase of cognition-targeted motor control training. In such patients, more educational time might be warranted, together with slow progression in low-grade and cognition-targeted exercises for altering the patient’s beliefs about the interplay between pain and movement.

In addition, it should be recognized that the general approach may not be suitable for all patients with CSP. For instance, special mental health expertise may be needed independently or conjointly to help CSP patients showing evidence high levels of pain-associated distress or psychologically-mediated disability. In general, large-scale studies are required to identify treatment predictors or subgroups that benefit most. Such work could help to contextualize the
overall clinical value of the approach, and perhaps assist in the further development of an individualized patient-centered approach.

Conclusions

The brain of patients with CSP differs from the ‘healthy’ brain in structure and function: besides impaired motor control of spinal muscles, patients with CSP also present with hyperexcitability of the central nervous system and brain abnormalities like decreased brain matter density. Still, the exact nature of the latter remains to be established as brain grey matter density and volume in patients with acute (spinal) pain require in depth-studying. In order to adopt the treatment for the brain abnormalities seen in patients with CSP, a treatment comprising of therapeutic pain neuroscience education followed by cognition-targeted motor control training can be applied. Therapeutic pain neuroscience education is ongoing throughout exercise therapy and motor re-education. Given the evidence that novel motor-skill training is associated with rapid changes in cortical excitability as well as cortical reorganization, this training type is considered relevant for treating patients with chronic musculoskeletal pain.
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Figure. The modern neuroscience approach to chronic spinal pain.