THE ROLE OF MOTOR LEARNING AND NEUROPLASTICITY IN DESIGNING REHABILITATION APPROACHES FOR MUSCULOSKELETAL PAIN DISORDERS

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Introduction

Cortical neuroplasticity is an intrinsic neurophysiological feature that occurs dynamically throughout life and can be defined as a morphological or functional change in the neuronal properties, such as strength of internal connections, altered representational patterns or a reorganization of neuronal territories (Calford, 2002; Sanes and Donoghue, 2000). The extent of cortical neuroplastic changes has been shown to be a key neurophysiological feature that facilitates the level of functional recovery. Rehabilitation efforts that attempt to maximize the extent of cortical neuroplastic changes stand to provide the greatest potential for rehabilitation success. Although these notions are established in neurological rehabilitation, they have yet to be fully incorporated into motor rehabilitation strategies for patients with musculoskeletal pain disorders. Since altered motor performance may be a factor for the maintenance of pain, motor rehabilitation approaches aimed at re-establishing normal motor strategies are a fundamental aspect of treatment of musculoskeletal pain disorders. This brief review discusses the cortical neuroplastic changes that have been shown to occur in association with pain and the role of novel motor skill training in the rehabilitation of patients with musculoskeletal pain. The aim is to highlight key components of motor skill training strategies that stand to provide the greatest potential for rehabilitation success.

Cortical Neuroplasticity and Recovery of Function

Patients with musculoskeletal pain, in comparison to healthy individuals, have functional changes (reorganization) of the neuronal properties in the sensorimotor system representing the muscles most affected by pain. For example, patients with low back pain (LBP) have reduced cortical spinal drive in the lumbar spinal muscles (Strutton et al., 2005) and a shift in the representation of the lower back muscles in the somatosensory cortex (Flor et al., 1997) Additionally, a topography study of transversus abdominis responses to transcranial magnetic stimulation (TMS) in patients with recurrent episodes of LBP, showed a posterior and lateral shift in the center of gravity (CoG) and a greater representation of the transversus abdominis in the primary motor cortex, indicative of cortical reorganization, in comparison to healthy individuals (Tsao et al., 2008). The most intriguing finding, however, was that patients showed a delay in the activation of transversus abdominis EMG during a rapid arm movement task and this delay was correlated to the extent of MI reorganization. Moreover, it was recently shown that LBP patients who participated in a motor skill training regime showed a reversal of the location of the CoG towards that previously demonstrated for healthy individuals (Tsao et al., 2010). These findings suggest that the cortical neuroplastic changes associated with pain may be reversed by motor skill training.

Motor Skill Training

In healthy individuals, novel motor skill training, in contrast to passive assistance or repetitions of general exercise, has been specifically associated with improvements in task performance and increased representation of the trained muscle in the primary motor cortex (MI) (Svensson et al., 2003b; Pascual-Leone et al., 1995; Karni et al., 1995). For example, one-week of novel tongue-task training was associated with an increased motor representation of the tongue muscle and increased cortical excitability of the tongue MI, as measured by TMS (Svensson et al., 2003b)(Figure 1). Similar increases in cortical excitability have also been demonstrated for the hand MI following 2-4 weeks of novel motor training of the hand (Koeneke et al., 2006). Furthermore, there is evidence to suggest that neuroplastic changes in the MI occur over shorter training intervals. Improvements in motor performance and rapid changes in cortical excitability of the tongue MI have been shown to occur immediately following 15 min of novel tongue-task training (Boudreau et al., 2007). Similar findings have been reported for training of a novel hand task (Classen et al., 1998; Boudreau et al., 2010a).

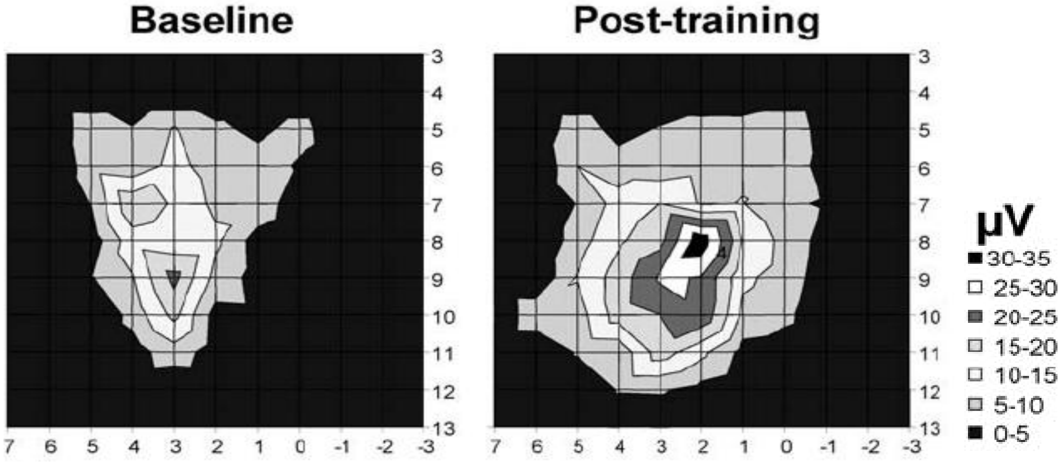

Figure 1

Given the evidence that rapid changes in cortical excitability as well as cortical re-organization occur in association with novel motor skill training, this training type may be relevant for treating patients with musculoskeletal pain. A common clinical approach that has been shown to be effective in the management of musculoskeletal pain disorders involves training the activation of a delayed or inhibited muscle with repeated isolated voluntary contractions (Falla et al., 2007b; Jull et al., 2008; Jull et al., 2009; Richardson et al, 1998) For example, neck pain patients encouraged to repeatedly activate the deep muscles independently of the more superficial muscles, constitutes a novel motor task (Falla et al., 2007b; Jull et al.,2008). The rationale for using this approach is based on the principle of novel motor skill training, which places emphasis on improved performance of a movement component rather than the simple execution of a sequence of movements (Fitts, 1967). This approach may also promote the cortical neuroplastic changes that occur in association with the learning stages of an untrained functional tasks and lead to improvements in motor behavior or performance, such as those observed by Tsao et al (2010).

There are, however, additional key components in motor skill strategies that have recently surfaced and may provide a means to optimize rehabilitation success.

Optimizing Rehabilitation Success

Non skilled training does not achieve the same effect as skilled training

The ability to target a specific component of movement requires greater skill and increased levels of attention and precision than contraction of all muscles (e.g., strength training). In agreement with these observations motor skill training coupled with strength training does not promote greater cortical neuroplastic changes in the MI than motor skill training alone (Remple et al., 2001) (Figure 2). These findings supplement the data from patients with LBP which showed that reorganization of the MI occurs following isolated training of the transversus abdominis muscle and not following a common exercise walking task (Tsao et al., 2010). Furthermore, the improvements in the amplitude and speed of activation of the deep cervical flexor muscles which occurs with isolated training of the deep cervical flexor muscles in patients with neck pain, does not occur with general strengthening exercise (Jull et al., 2009).

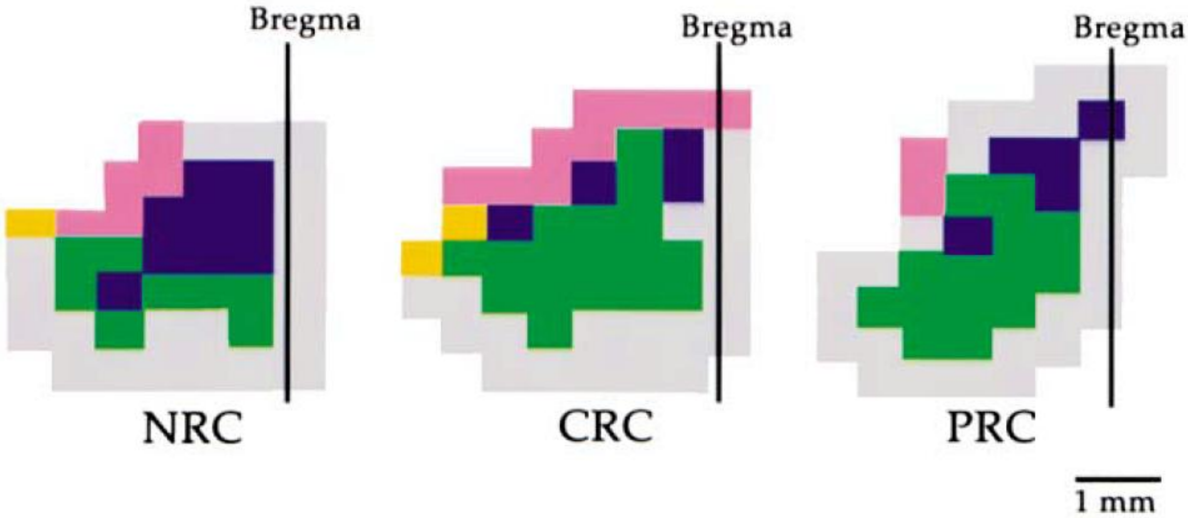

Figure 2

Pain can hinder the cortical neuroplastic changes associated with novel motor skill acquisition

To date, studies which have examined the effects of acute experimental pain have revealed that, as with novel motor skill training, pain can rapidly alter the cortical excitability of the MI (Cheong et al., 2003; Le Pera et al., 2001; Svensson et al., 2003a; Farina et al., 2001). Further research, however, is required to discern the features of the cortical neuroplastic changes associated with novel motor skill training and that which occurs in association with experimental or chronic pain. In contrast to the rapid changes associated to novel motor skill acquisition, the changes in cortical excitability that occur in association with acute pain are not necessarily consistent between the muscle groups represented in the MI. For example, noxious electrical stimulation of the finger induces an increased excitability of the hand MI but a simultaneous decreased excitability of the proximal (upper arm) muscles (Kofler et al., 1998). These pain-related changes in excitability of the MI may contribute to protective motor control strategies (e.g., reduced range of motion) that can occur in association with a painful limb or muscle and are consistent with alterations in muscle strategies observed following experimentally induced muscle pain (Graven-Nielsen et al., 1997; Falla and Farina, 2008) . For example, when pain is acutely induced in the neck muscles of healthy subjects, the coordination among neck muscles is substantially altered (Falla et al., 2007a). Similar findings are observed in patients with chronic musculoskeletal pain. Patients with chronic neck pain show augmented activity of the superficial neck muscles (Falla et al., 2010; Falla et al., 2004; Jull et al., 2004), possibly as an attempt to increase neck stiffness (Danna-Dos-Santos et al., 2007) and compensate for weakness of the deeper neck muscles (Falla et al., 2004).

Notably, acute experimental pain has been shown to suppress the rapid increases in cortical excitability of the MI and interfere with the incremental gains in task performance that would otherwise occur in association with a single-session of novel tongue-task training in humans (Boudreau et al., 2007) (Figure 3). The notion that pain may hinder novel motor skill acquisition is in agreement with observations at various behavioral levels for chronic pain patients. Increased stress responses during a cognitive task (Thieme and Turk, 2006), reduced cognitive performance (Apkarian et al., 2004; Dick and Rashiq, 2007; Moseley, 2004b; Moseley, 2004a; Weiner et al., 2006), reduced quality of sleep (Roehrs and Roth, 2005), and attention deficits (Eccleston et al., 1997; Grisart and Plaghki, 1999), can affect learning. Taken together, these findings suggest that motor skill training should be performed in a pain-free manner in order to optimize success. The type, load and frequency of exercise should be tailored towards the patient to ensure that this criterion can be met.

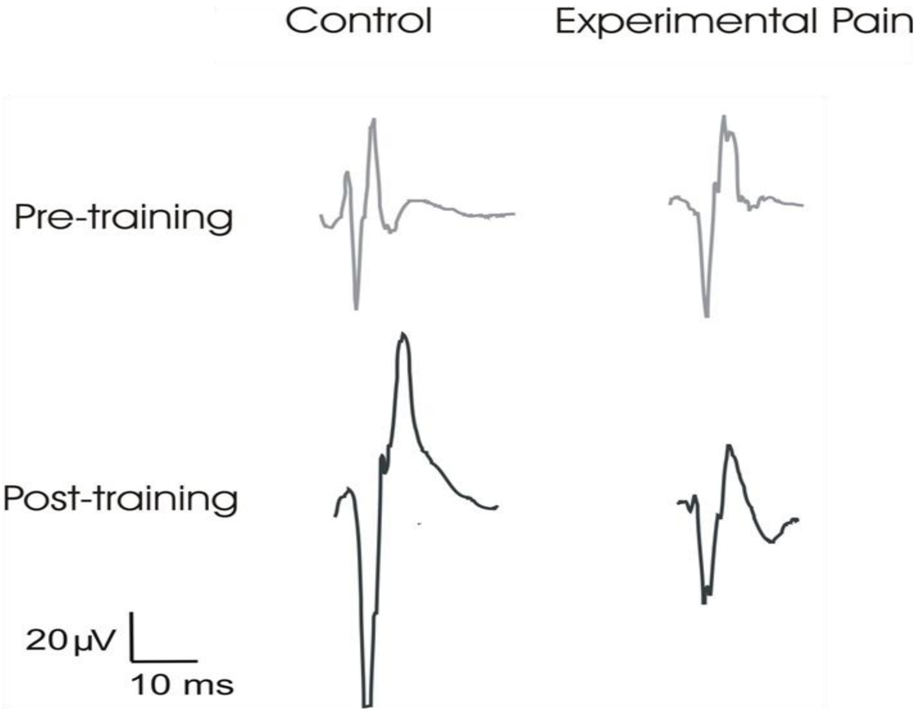

Figure 3

Motor skill training can protect against the cortical neuroplastic changes associated with pain

While the experimental pain studies undoubtedly provide a link between pain and altered motor control (Falla and Farina, 2008; Graven-Nielsen and Arendt-Nielsen, 2008), there is less evidence to support the initiation of pain as a consequence of altered motor control. It can be speculated that deficits in motor control of the spine lead to poor control of joint movement, repeated microtrauma and thus, eventually to pain (Panjabi, 1992a; 1992b). For example, augmented activity of the upper trapezius and the levator scapulae muscles, due to a poor working posture of the neck or of the arms, may over time increase compressive loads on the cervical segments and initiate a painful neck condition. Likewise, inhibition of the deep abdominal muscles may affect the stability and posture of the lumbar spine increasing the likelihood of LBP (Hodges and Moseley, 2003). Although there is no consensus on the cause-effect relationship between altered motor control and clinical pain, there is certainly a consensus that experimental or clinical pain is associated with altered motor control.

A series of studies performed in spinalized rats has revealed that associative motor training prior to acute experimental pain can reduce the extent of neuroplastic changes in the spinal cord that would otherwise occur (Ferguson et al., 2006; Hook et al., 2008). Although these findings have yet to be reproduced in human studies, the notion that motor training can reduce the extent of cortical neuroplastic changes associated with pain is congruent with the finding that acute pain reduces the neuroplastic changes associated with motor learning (Boudreau et al., 2007). In summary these findings suggest that novel motor skill training should be advocated upon the first presentation of musculoskeletal pain symptoms so as to reduce the risk of further and unfavorable neuroplastic changes that are known to occur in association with pain.

Encourage cognitive effort

Goal-oriented or ‘cognitive’ effort significantly contributes to the extent of cortical neuroplastic changes associated with novel motor skill acquisition. For example, the performance of a goal-oriented sequential finger-tapping task over 5 days is associated with an increased representation of the trained muscle in the MI compared to a protocol that require mental rehearsal of the finger-tapping task or a random non goal-oriented finger-tapping protocol (Pascual-Leone et al., 1995). Moreover, the performance of a complex finger-tapping task results in additional areas of cortical activation, as measured by fMRI, when compared to a simple finger-tapping task (Sadato et al., 1996). Further, the amount of overlapping cortical territories in the MI that is altered with training is greater when training of simple finger and wrist movements are paired with fine (finger sequence learning) rather than gross (squeezing a sponge) motor skill training (Hlustik et al., 2004). In agreement with these human studies, animal studies show that increasing the complexity of a skilled reaching task results in a relatively larger expansion of the digit and wrist representations, as defined by intracortical microstimulation of the MI (Kleim et al., 2002). In summary, these findings suggest that slowly evolving the complexity of the novel motor skill task over the duration of rehabilitation training may encourage cognitive effort and enhance the cortical neuroplastic changes that are known to occur in association with novel motor skill acquisition.

Quality versus quantity

A detailed analysis of the motor behavior associated with novel motor skill training has revealed that significantly different within-session gains in an initial motor-skill training session do not differentially affect the time course of the initial or overall motor performance in subsequent training sessions (Boudreau et al., 2010b). The time course of these gains in overall motor performance were similar for protocols which consisted of 72 or 144 task-repetitions over a period of 15 and 30 min, respectively (Boudreau et al., 2010b) and furthermore, were consistent with a previous tongue-task training protocol that consisted of 216 within-session task-repetitions over 60 min (Svensson et al., 2003b). Together, these two studies provide evidence that extended within-session task repetitions of a novel motor skill may not facilitate additional gains in overall motor performance. Such findings suggest that excessive repetitions of a motor task within a training session may not result in additional benefits. This notion may be extended upon consideration that rapid changes in cortical excitability are already apparent following short (60-70 within session task-repetitions over a period of 10-15 min) training intervals (Boudreau et al., 2007; Boudreau et al., 2010a). Accordingly, task-repetitions should be limited in order to ensure that factors such as fatigue or pain are minimized. Further, the quality of training appears more important for improving the performance of a motor task. For example, changes in the timing of activation of the transversus abdominis muscle have been correlated to the quality of training and are associated with improvements in self-reported pain and function (Tsao et al., 2010). These findings direct the clinician to focus on the quality rather than the quantity of training to optimize rehabilitation.

Conclusion

Rehabilitation efforts that attempt to maximize the extent of cortical neuroplastic changes stand to provide the greatest potential for rehabilitation success. Clinical and experimental findings suggest that quality motor skill training that encourages cognitive effort should be performed with a limited number of task-repetitions such that fatigue and pain are minimized in order to optimize rehabilitation of patients with musculoskeletal pain.

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FIGURE LEGENDS

Figure 1: Cortical motor maps of the face MI which show a significant expansion of the tongue muscle representation following one-week of daily novel tongue-task training (Svensson et al., 2003).

Figure 2: Cortical motor maps of the rat MI which show that skilled forelimb (CRC) and skilled power reaching paired with power or strength demand (PRC) results in significant increases in the representation of the forelimb (from blue to green) when compared to a non-reaching (NRC). These motor maps also show that there are no additional cortical neuroplastic changes that occur for the strength protocol (Remple et al., 2001)

Figure 3: Motor evoked potential (MEP) elicited in the tongue showing an increase in MEP amplitude following novel motor skill training and no increases in the MEP amplitude when novel motor skill training is performed in the presence of experimental pain (Boudreau et al., 2007).