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# Motor control and the management of musculoskeletal dysfunction

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## Abstract

This paper aims to develop understanding of three important motor control issues—feedforward mechanisms, cortical plasticity and task-specificity and assess the implications for musculoskeletal practice.

A model of control for the reach-to-grasp movement illustrates how the central nervous system integrates sensorimotor processes to control complex movements. Feedforward mechanisms, an essential element of motor control, are altered in neurologically intact patients with chronic neck pain and low back pain. In healthy subjects, cortical mapping studies using transcranial magnetic stimulation have demonstrated that neural pathways adapt according to what and how much is practised. Neuroplasticity has also been demonstrated in a number of musculoskeletal conditions, where cortical maps are altered compared to normal. Behavioural and neurophysiological studies indicate that environmental and task constraints such as the goal of the task and an object's shape and size, are determinants of the motor schema for reaching and other movements.

Consideration of motor control issues as well as signs and symptoms, may facilitate management of musculoskeletal conditions and improve outcome. Practice of entire everyday tasks at an early stage and systematic variation of the task is recommended. Training should be directed with the aim of re-educating feedforward mechanisms where necessary and the amount of practice should be sufficient to cause changes in cortical activity.
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## 1. Introduction

An understanding of motor control is central to management of patients with a damaged central nervous system (CNS) but recent research (Falla et al., 2004a, b; On et al., 2004) indicates it is also of great importance in the management of musculoskeletal dysfunction in patients with an intact CNS. Historically, an in depth understanding of motor control has not been central to musculoskeletal practice, although discussion of certain motor control issues in a recent authoritative text (Boyling and Jull, 2004) indicates that this is changing. This paper aims to develop understanding of three important motor control issues—feedforward mechan-

isms, cortical plasticity and task-specificity. First, a model is presented that illustrates how the sensorimotor processes needed to perform a typical movement are integrated. Then, evidence is presented indicating that the feedforward mechanisms used to monitor movement and the functional organization of the cortex can change in response to musculoskeletal dysfunction. The authors also show that the motor plan generated depends on the specificity of the task being performed. The implications of these findings for management of patients with musculoskeletal dysfunction are discussed.

## 2. A model of motor control for reach to grasp

In this section, a model of the control of reach to grasp movements will be used to illustrate the integration of

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sensorimotor processes in performing a movement. Reach to grasp has been chosen because there is sufficient knowledge available to build up a representation of CNS control, and because it is an essential everyday movement.

Research on CNS control of reach-to-grasp in healthy subjects is encapsulated in a model shown in Fig. 1 and this model is supported by substantive data from both computer simulation and human studies (Hoff and Arbib, 1993). The model is an example of a 'motor program', defined as ''a set of motor commands that is pre-structured and that defines the essential details of a skilled action'' (Schmidt and Wrisberg, 2000). It is likely that we use motor programs for many actions (Schmidt and Wrisberg, 2000). According to this model, the reach is planned with respect to the end goal of the movement, by ensuring that the time to close the hand from maximum aperture is constant. In the model, it is proposed that the parameter used to control the path of the hand through space is the third derivative of wrist position, called jerk (velocity is the first derivative and acceleration the second). The CNS tries to minimize the amount of jerk during the reach. Two important parameters for controlling the movement are therefore, time to close the hand and minimum jerk. There is a two-way interaction between the neural processes controlling transport and grasp, so that the expected duration to the target, of each of these elements, is monitored and adjusted to ensure temporal matching.

Although there is much evidence that reaching movements are planned in advance of the movement via such a motor program (e.g. Jeannerod, 1988), there must be ongoing monitoring of transport and grasp, especially if conditions change after movement onset or where more accurate movements are required. The model proposes two mechanisms for this function—



Fig. 1. An example of a co-ordinated control program made up of three motor schemas. Whichever schema needs more time sets the total duration specified by the time-based coordination model (Reproduced by kind permission of Elsevier, Hoff and Arbib, 1993).

feedback and feedforward (anticipatory control). Feedback from vision and proprioception about hand location and hand aperture is useful in the latter part of the reach, since the minimum time needed for a response to this information is estimated at about 100 ms (Jeannerod, 1988). Before this, feedforward mechanisms are responsible for on-line movement adjustments (Desmurget et al., 1999). There is evidence that the feedforward mechanism for reaching works by comparing target position with an instantaneous internal predictive estimate of hand position (efferent copy), and this information is used to modify the ongoing motor command (Desmurget et al., 1999; Desmurget and Grafton, 2000).

## 3. Evidence of disruption to feedforward mechanisms in musculoskeletal dysfunction

### 3.1. Feedforward mechanisms in healthy subjects

As well as in grasp, feedforward mechanisms have been identified in a number of muscle groups involved in other movements. Most of the empirical studies consider muscle activity that occurs 100 ms before to 50 ms after the onset of the prime mover to represent feedforward control (Aruin and Latash 1995). In the reach-to-grasp model described earlier, feedforward operated to adjust the position of the hand. Feedforward also occurs in order to move the centre of mass prior to limb displacement, maintain the stability of the vestibular system and visual field during neck movement, prepare for the anticipated reactive forces or to act synergically to maintain local muscular stability surrounding spinal joints during large torque generating movements (Falla et al., 2004b). Feedforward control is ongoing during the movement as well as occurring before the movement begins.

In healthy subjects Falla et al. (2004b) have shown that the sternocleidomastoid and cervical extensor muscles demonstrate feedforward activation during rapid unilateral and bilateral upper limb flexion, extension and abduction. These muscles were activated within 50 ms of the onset of deltoid muscle activity. The authors suggest that as well as opposing the reactive forces during arm movements, this mechanism is necessary to achieve stability for the visual and vestibular systems during movement.

### 3.2. Feedforward mechanisms and musculoskeletal dysfunction

Falla et al. (2004a) compared onset of neck muscle activation in people with chronic neck pain to healthy subjects during flexion and extension of the upper limb. In contrast to healthy subjects, during flexion, activation
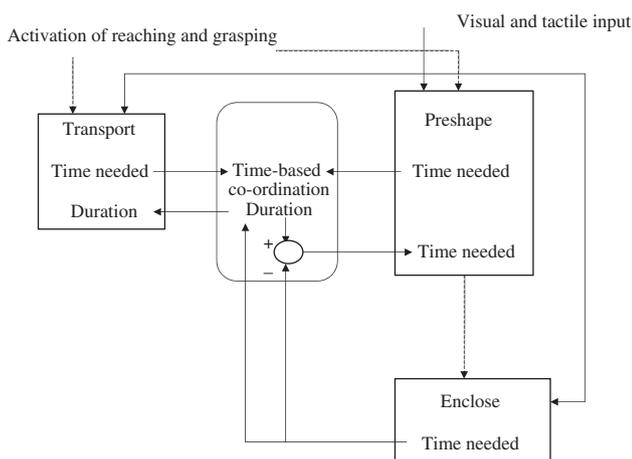
of deep cervical flexors, contralateral sternocleidomastoid and anterior scalene muscles were significantly delayed in the patients. Further exploration of feedforward mechanisms could examine more purposeful movements, as it is not known whether similar findings will occur with tasks such as reaching for an object or combing the hair.

Feedforward mechanisms have been shown to be compromised in the trunk muscles in the presence of low back pain (Hodges, 2001; Hodges et al., 2003) and isometric muscle fatigue (Allison and Henry, 2002). Also, the feed-forward activation of transverses abdominus was found to be delayed in the presence of long-standing groin pain (Cowan et al., 2004). Feedforward mechanisms were even found to be absent during rapid upper limb activity in patients with chronic recurrent low back pain (Hodges and Richardson, 1999). The exact mechanism is poorly understood but the loss of anticipatory control of the proximal segment/spine during limb movement (changing the centre of mass) may adversely affect articular stability. From in vitro studies Panjabi (1992) proposed that 80% of cervical stability was attributable to the muscular system (active subsystem) compared with the passive stability of ligaments and capsule, etc. Where muscular stability is compromised additional strain may be placed on the articular structures further exacerbating instability and/or pain. Alternatively, the pain itself might cause an inhibition of feedforward activity. Hodges et al. (2003) provide some evidence for this by demonstrating that experimentally induced pain can change the feedforward activity of trunk muscles in anticipation of arm movements. Also, afferent information to the CNS encapsulates more than nociceptive information and the influence of factors such as altered proprioception, muscle length and muscle tension, on feedforward activity, needs to be elucidated.

For optimal movement a combination of both feedback and feedforward processes are likely to be required (Desmurget and Grafton, 2000). There has been little work to date considering the implications for clinical practice of altered feedforward mechanisms in patients with dysfunction. For example at what stage of neuromusculoskeletal dysfunction do these mechanisms begin to manifest themselves? Do they follow the onset of pain or more importantly do they precede the pain? How may they be rehabilitated? The authors are aware of only one study to date that has considered whether a loss of feedforward control can be rehabilitated with physiotherapy. Cowan et al. (2003) reported that a 6-week conventional programme of physiotherapy for 40 subjects with patellofemoral pain, including specific muscle retraining, biofeedback and taping aimed at restoring coordination and control of the vasti muscles, was effective in restoring feedforward recruitment of these muscles. The programme demonstrated that physiotherapy can be effective in the restoration of feedforward mechanisms. However, it was not clear which component of the treatment was responsible. Also, EMG measurements were taken during a 'rise' and 'rock' task, which, although reliable in the laboratory, may not closely resemble use of the vasti muscles in everyday activities. Despite good support for the use of management approaches which utilize aspects of motor control theory through muscle retraining programmes for rehabilitation of lumbar muscles (O'Sullivan et al., 1997) and cervical muscles (Jull et al., 2002), there is a paucity of studies specifically evaluating the effect of therapy on feedforward control within the spine.

## 4. Evidence relating to cortical plasticity

### 4.1. Practice and cortical plasticity

Recent research has indicated that the functional organization of the primary motor cortex, rather than being fixed, can change in response to practice. The commonly used method in such studies is by measuring the motor evoked potentials (MEPs) in response to transcranial magnetic stimulation (TMS). TMS is non-invasive and is delivered via a magnetic coil placed near the skull. A cortical map is constructed indicating cortical representation of muscles or movements.

One study compared muscle representations in both hemispheres in people skilled at a volleyball 'strike' movement and in runners (Tyc et al., 2005). MEPs were recorded from the proximal medial deltoid and distal extensor carpi radialis muscles during magnetic stimulation, while subjects were seated and either aiming to hit a target or perform static wrist extension. The size of the cortical map for middle deltoid was larger for volleyballers than for runners. Furthermore, the total size representation for both muscles was larger for the dominant arm than the non-dominant arm, in the volleyball group. This finding supports the hypothesis that activity drives cortical plasticity, since there is different cortical organization between two groups with different levels of skill.

Even a small amount of practice can cause cortical changes. Hayashi et al. (2002) found that the amplitudes of motor-evoked potentials and the size of the cortical map increased dramatically after 100 repetitions of simple index finger abduction. Such quick changes are likely to be due to changes in synaptic efficiency from a strengthening of existing synapses (Hayashi et al., 2002). With larger amounts of practice however, changes in the balance of excitation and inhibition may induce anatomical changes in synaptic organization.

There is also evidence that this functional organization of somatosensory cortex may change dynamically according to and during task requirements. Braun et al.

(2001) compared organization of somatosensory cortex when subjects were doing the well-learned task of writing compared to at rest. During the two conditions a tactile sensation with force of 1.6 N was delivered to the 1st and 5th digits. Cortical representations of the stimulated fingers were measured. The cortical representations of each finger were further apart during writing than at rest, indicating functional reorganization. The authors proposed that there are different pre-existing maps, and the somatosensory cortex switches rapidly between them according to task requirements. This idea is supported by other studies of cortical plasticity (e.g. Karni et al., 1998).

### 4.2. Musculoskeletal dysfunction and cortical plasticity

Changes in cortical maps have also been measured in a number of musculoskeletal conditions including chronic knee (On et al., 2004) and back pain (Flor, 2003), nerve injury (Braune and Schady, 1993), rheumatoid arthritis (Jones and Derbyshire, 1997), fibromyalgia (Salerno et al., 2000), amputation (Braune and Schady, 1993), and also with immobilization (Zanette et al., 2004).

In patients with patellofemoral pain syndrome, On et al. (2004) found that the amplitude of the MEP for vastus medialis oblique (VMO) and vastus lateralis when TMS was applied was significantly increased compared to control subjects, especially in the VMO. It was argued that through a restriction of movement induced by pain, proprioceptive input to the CNS may have been reduced. The larger MEPs of the stabilizing muscles of the patella may be a response to these changes. In chronic back pain also, Flor (2003) have documented an expansion of the cortical representation related to nociceptive input and also an increased cortical excitation.

Some of the changes seen after nerve injury may be due to cortical plasticity. One group of patients with microsurgically repaired median or ulnar nerve transections was subjected to tests of thermal and pain thresholds, vibration and tactile thresholds, stimulus–response curves, two point discrimination and locognosia (location of tactile stimuli) (Braune and Schady, 1993). The fingertips had better tactile sensitivity and recovered normal localization capacity before more proximal areas. As they should have the least reinnervated mechanoreceptors these findings were therefore attributable to central changes.

### 5. Task specificity of control of everyday actions

There is ample evidence that the motor control of everyday actions is task-specific. For example, the kinematics of reaching movements requiring a pincer grasp, are characterized by a longer deceleration phase than those using whole hand grasp, allowing more time to adjust for potential spatial error (Bootsma et al., 1994). Neurophysiological evidence also demonstrates selective cortical activation for different types of grasp (Rizzolatti et al., 1988).

Accordingly, studies have been undertaken to assess the effectiveness of delivering task-specific motor training to neurologically impaired patients. For example, in a well-designed randomized controlled trial, stroke patients' sitting balance was trained using systematically varied reaching tasks such as changing the speed, direction, object weight, seat height and amplitude of the movement (Dean and Shepherd, 1997). The programme resulted in significantly better performance compared to a placebo control group who received sham training. Other studies in patients with stroke have also demonstrated the positive effect of task-specific training (Richards et al., 1993; Dean et al., 2000; Blennerhassett and Dite, 2004). Task-specific training is likely to also enhance the outcome for musculoskeletal conditions, but as yet this has not been systematically evaluated.

The studies reviewed earlier demonstrate cortical changes in response to practice of specific movements, in neurologically intact subjects. Task-specific training is therefore likely to be useful in the rehabilitation of people with musculoskeletal dysfunction with intact CNS, to gain optimal skill acquisition.

### 6. Implications clinical practice

The evidence presented points to several suggestions for musculoskeletal clinical practice. First, our general argument is that an understanding of the motor control for the task or movement that is targeted for rehabilitation is essential, including at the very least the processes involved in generating and monitoring movement commands and how these are integrated with feedforward and various sensory feedback modalities. For example, the evidence on cortical plasticity and task specificity suggests that practice of part of a task such as wrist extension, may not activate the same neuronal network as practice of wrist extension within the whole task such as reaching. Instead the part practice would develop and strengthen a motor programme for 'wrist extension'. This may cause the lack of carry over between exercises and everyday activity, often seen in clinical practice. Therefore, it is recommended that functionally oriented exercise be incorporated as early as possible in the management, rather than after many repetitions of component parts of movements. In this way, the necessary feedforward and feedback mechanisms can be integrated with the appropriate motor programme, while function of the damaged part is

regained. This contention needs to be formally evaluated by empirical research, to see whether outcome is more effective or is achieved more quickly.

Second, because of the task specific nature of cortical control, therapists should consider asking patients to practice variations on the particular task or movement being rehabilitated, to ensure that the cortical connections necessary for different task requirements are also developed or strengthened. Otherwise, it is possible that the person's performance might only be sufficient in some task conditions, and not others. For this, previous studies with stroke patients could lead the way, where factors such as speed, direction, object weight, seat height and amplitude of the movement could be varied systematically during practice (Dean and Shepherd, 1997). For example, a patient with a history of pain on cervical spine extension may be advised to extend the head with the deep neck flexors activated. This exercise could be performed while taking something out of a cupboard (task-specific practice), and within this practice, the speed, range of motion, loading, start position (head in rotation or side flexion), could be varied to strengthen the cortical connections associated with each variation of that task.

Changes in feedforward that accompany some musculoskeletal conditions must be important for the patient's functional outcome and the risk of future reoccurrence of the condition. It would seem very useful for therapists to know or work out the feedforward activity that would normally precede or occur during the movement being trained. In some cases, evidence will be available to describe the altered feedforward mechanisms for the condition, such as in the case of chronic neck pain (Falla et al., 2004a). It may be possible to re-educate the appropriate feedforward mechanisms (Cowan et al., 2003). In stroke rehabilitation, anticipatory postural adjustments can be retrained by identifying the necessary postural muscle activity and choosing an amplitude of movement for practise, which is just beyond the patient's control, thereby challenging the CNS to increase the postural activity. Movement amplitude is slowly increased as performance improves. This approach may be useful in musculoskeletal rehabilitation. Another aspect is that if altered feedforward precedes the emergence of pain, it might be possible to predict which patients might develop a painful condition, and institute intervention to prevent it.

Last, an important issue is the recognition of the flexible nature of cortical connections. Changes in cortical maps can occur relatively quickly (Hayashi et al., 2002). Implications from this are that injured people presenting to physiotherapists may already have altered cortical maps if the condition has caused them to move differently from normal, but that it might be possible to reverse these changes with practice. The

amount of practice necessary may be further elucidated by research that carefully records the amount of practice for a particular condition with particular chronicity, and uses measures of both cortical activity and motor performance to measure outcome. This approach could be expected to provide guidelines for amount of practice, which could be adapted to suit individual presentations of the condition. Conclusions about the amount of practice necessary to alter cortical connections will also need to be combined with guidelines for the amount of practice necessary to cause changes in strength or endurance, which are more commonly considered in musculoskeletal practice.

## Clinical messages

- Remedial practice of movement components should be practised within the whole task, from the outset, to encourage desired cortical activity.
- Task practice should be systematically varied.
- The possibility of changes in feedforward control should be considered and retrained if possible.
- Practice should be sufficient to cause changes in cortical activity.

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