# Sensori-motor integration during different finger movements and evidence for reorganisation in subjects with a chronic partial nerve entrapment of the median nerve at the wrist in man

by

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# Abstract

In part A of the thesis, experiments were performed to determine whether the reflex effects of digital nerve stimulation on first dorsal interosseous muscle (1DI) are contextually influenced. It was found that voluntary and passive finger movement significantly reduced the size of the transcortical E2 reflex component. Reflex components I1 and E1 were unaltered. The simultaneously recorded contralateral somatosensory cortical evoked potential (SEP) was significantly reduced, suggesting that 'gating' of the afferent input to sensory cortex is involved in reducing the size of the E2 reflex component. The reduction in the cortical SEP components observed during passive finger movement suggests that sensory feedback from the periphery contributes to 'gating' of the afferent input. Subsequent experiments involving attentive and non-attentive finger tasks were performed. It was found that the E2 and I1 components of the CMR and cortical SEP components were selectively altered in a task dependent manner. The E1 reflex component was unaffected. In the final experiment, the reflex effects of distant digital nerve stimulation (little finger) on 1DI during two movement tasks were examined. It was found that the transcortical E2 reflex component radiated in a task dependent manner. Reflex components E1 and I1 were unaltered.

In part B, recordings were obtained from subjects with a chronic partial nerve entrapment of the median nerve at the wrist (C.P.N.E). The aim of these experiments was to determine whether the reflex effects of digital nerve stimulation on 1DI is reorganised in the hand in response to the C.P.N.E. It was found that the pattern of the reflex effects of digital nerve stimulation in 1DI was altered in the subjects with C.P.N.E. Stimulation of a distant (little) finger produced clear reflex changes in the 1DI muscle not evident in healthy control subjects, showing that reflex reorganisation has occurred following C.P.N.E.

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# List of commonly used abbreviations

| | |
|---|---|
| CMR | Cutaneomuscular reflex |
| 1DI | First dorsal interosseous muscle |
| SEP | Somatosensory evoked potential |
| S1 | Primary sensory cortex |
| M1 | Primary motor cortex |
| MVC | Maximium voluntary contraction |
| ABD | Abduct |
| CTS | Carpal tunnel syndrome |
| NCS | Nerve conduction studies |
| SNAP | Sensory nerve action potentials |
| EMG | Electromyogram |
| EEG | Electroencephalogram |
| % EMG Modulation | Percentage EMG Modulation |
| CNS | Central nervous system |
| MAP | Motor action potential |
| SEP | Somatosensory evoked potential |
| CPNE | Chronic partial nerve entrapment |
| PTN's | Pyramidal tract neurones |
| CM cell | Cortico-motoneurone cell |
| SEF's | Somatosensory magnetic fields |
| fMRI | Functional magnetic resonance imaging |
| DCN | Dorsal column nuclei |
| VPL | Ventral posteriorolateral nucleus |
| CTS | Carpal tunnel syndrome |
| RF's | Receptive fields |
| MEP | Motor evoked potential |

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This thesis is dedicated to Jeff.

# General introduction

## Thesis overview

This thesis reports the results of a number of experiments designed to investigate different aspects of reflex integration by recording the cutaneomuscular reflex (CMR) response and cortical somatosensory evoked potential (SEP) in health and disease in man. The thesis is divided into two parts.

In part A the integration of the sensori-motor system during different finger movements in a number of healthy adults is examined. In section one the effect of voluntary and passive finger movement upon the CMR recorded from the first dorsal interosseous muscle (1DI) and the cortical somatosensory evoked potential recorded from the contralateral primary sensory cortex (S1) is investigated to determine whether the reflex effects of digital nerve stimulation on 1DI are contextually influenced. The results are discussed in relation to available evidence on factors controlling the reflex effects of digital nerve stimulation during different types of finger movement.

The second section describes the effect of attentive and non-attentive finger movement tasks upon the cutaneomuscular reflex response recorded from the 1DI muscle and cortical SEP recorded from the contralateral S1 performed to determine whether 'attention' to a stimulus alters reflex responsiveness to digital nerve stimulation. The results are discussed in light of current evidence relating to the attentional effects within the central nervous system (CNS) upon the control of finger movement during different tasks.

The third section describes the reflex effects of distant digital nerve stimulation on the 1DI muscle during two different finger movement tasks to investigate whether the pattern of radiation of reflex responsiveness to distant digital nerve stimulation is altered during two different finger movement tasks. The results are discussed in relation to factors controlling reflex responsiveness to digital nerve stimulation in man and in relation to the performance of different hand movements in healthy individuals.

Part B of the thesis describes changes in the distribution of the reflex effects of digital nerve stimulation on the 1DI muscle in individuals with a chronic partial nerve entrapment (CPNE) of the median nerve at the wrist not evident when compared to healthy individuals and attempts to relate the change in distribution of the reflex response to the impairment of hand function and the sensory symptoms experienced by individuals with a CPNE. The distribution of the reflex response of 1DI muscle to little finger digital nerve stimulation in a single subject with an amputation of the index finger, and a second subject with a trans-section of the median nerve are also described. These findings are discussed in the light of evidence of central nervous system 'plasticity' or 'reorganisation' in both human and animal studies.

## Historical overview

This thesis describes experiments designed to investigate how the reflex control of movement might be affected by the nature of the voluntary task being carried out, and how sensori-motor integration might be reorganised following a peripheral nerve lesion. The basic concepts of reflex and voluntary action and observations relating to their anatomical basis can be found in early medical texts. Galen (130-200 AD), for example describes experiments in which he observed that if the spinal cord of a pig was severed between the 3rd and 4th vertebrae the animal ceased to breath but if the cut was made lower down between the 6th and 7th vertebrae the animal continued to breath but both movement and sensation were lost below the level of the cut. In his writings he used these observations to explain the injuries sustained by gladiators in the arena (*Op. cit.* p19, Cohen, 1958). In addition by careful anatomical dissection, Galen discovered that nerves originated from the brain and spinal cord, and also that motor nerves arose from the spinal cord. From these findings he concluded that both the brain and spinal cord were vital in the production of voluntary movement (Bennett & Hacker, 2002).

The first ideas of a 'reflex' response did not clearly emerge until the 1600's when Descartes put forward the idea that some movements could be machine-like and automated in nature rather than 'voluntary' in his treatise '*Passions de l' Âme*' (1649). Descartes viewed the body as a machine that was organised by a ' controlling area ' (specifically the pineal gland believed to house the soul in the 1600's). He suggested that sensory information (which he called '*material animal spirits*' from the external world) was directed towards the pineal gland via the ventricles, interpreted, and then '*reflected*' to the appropriate part of the body via tubular hollow nerves where a response was generated. Recognising that some movements were involuntary Descartes described the blink reflex as an example of such a movement (Bennett & Hacker, 2002; *Op. cit.* p6, Brazier, 1969).

Building on these ideas Thomas Willis (1672) proposed that the spinal cord could be a centre for the relay of information between nerves. He stated that sensory impressions were carried by '*animal sprits* ' to the '*sensorium commune*' (which he placed in the corpus striatum) that went onto the higher centres of the brain where they were interpreted and processed into memories. A proportion of the '*spirits*' were also reflected into the muscles to produce a response (Bennett & Hacker, 2002; *Op. cit.* p31, Brazier, 1969).

In 1686, John Bohn performed the first experimental demonstration of a flexion reflex elicited by painful cutaneous stimuli using a decapitated frog. He found that when the skin of the frog was pinched, pricked or burnt there would be an automatic withdrawal of the limb. Bohn speculated that this was totally mechanical in nature (*Op. cit.* p20, Cohen, 1958). Taking these observations further the Reverend Stephen Hales (1733) performed the same experiments on a decapitated frog in which he similarly showed that he could get the frog's leg to withdraw in response to pinching of the skin. In addition he made the critical observation that this reaction was lost if the spinal marrow was destroyed (*Op. cit.* p32, Brazier, 1969).

It was not until 1765 when Robert Whytt published in his treatise *'On the vital and other involuntary motions of animals'* that the importance of the spinal cord in generating such reflex responses was fully appreciated. (*Op. cit.* p32-33, Brazier, 1969). In his treatise he repeated the experiments originally performed by Stephens Hales, showing the same observations. Furthering these observations he showed that if the strength of the stimuli is increased, the resultant reflex response spreads. He also reported the phenomena '*spinal shock*' (i.e. when a frog is decapitated it is rendered unreactive for approximately 15 minutes).

In 1784 Prochaska wrote a description that more clearly defined the term reflex. He used terms such as '*....reflexion of sensorial into motor impressions....*' to describe the nature of a reflex response, and also explained how the responses may be driven by involuntary or voluntary mechanisms (Zehr & Stein, 1999).

It was shortly after that Charles Bell (1811) published a short private leaflet that suggested that the posterior roots of the spinal cord were associated with unconscious sensory impression and involuntary movement (*Op. Cit.* P28-29, Brazier, 1969). In 1822 Francis Magendie demonstrated in dog experiments that if he cut the posterior roots of the spinal cord only sensory function was abolished, whilst cutting the anterior root of the spinal cord produced deficits only in movement (*Op. Cit.* p28-29, Brazier, 1969). Both Bell and Magendie had made the historic finding that the anterior located roots were involved with motor functions whilst the posterior roots were involved in sensory function, and is today known as the 'Bell-Magendie law'.

In 1833 Marshall Hall gave a full communication to the Royal Society which was published in Philosophical Transactions, titled *'on the reflex function of the medulla oblongata and medulla spinalis'* made on the basis of research performed on frogs and reptiles in which he elicited the flexion reflex to painful cutaneous stimuli to show that the nervous system is made up of segmental reflexes that he called *'reflex arcs'.* Hall also showed that such reflexes could be combined to produce more complicated movements which he called *'arcs of reflex function'*, both terms which are currently used today to describe reflex function (Hall 1833; Hall 1837; *Op. Cit.* p35-36, Brazier, 1969).

So by 1840 the reflex response had been demonstrated experimentally and had become more clearly defined, the importance of the spinal cord in generating the reflex and the origins of the motor and sensory roots of the spinal cord had been identified. However at this stage there was little understanding of the components needed to evoke a reflex response. Some microscopic observations regarding the spinal cord had been made. Alexander Munro (1783) had earlier described the anterior horn cells, and later Remak (1838) described non-medullated and medullated nerve fibres.

In 1850 Augustus Waller demonstrated that severing a nerve from the cell body caused the disconnected nerve fibre to degenerate (*Op. Cit.* p26, Brazier, 1969). Waller had found a way of tracing the path of the nerve fibres by employing staining techniques in both the CNS and PNS. This led to many experiments tracing the structure and connections of the nervous system.

At about the same time using the galvanometer, named after Galvani who revealed that animal nerve cells produced electricity, duBois-Reymond recorded the electrical activity generated by muscle contraction, and later in 1868 Bernstein confirmed the idea that sensory information was conveyed as a self propagated '*action current*' along the nerve (*Op. Cit.* p21-23, Brazier, 1969).

## Cutaneous reflexes

The first demonstration of the flexion reflex to painful cutaneous stimuli in the early eighteenth century signalled the beginning of an extensive investigation into the nature of the cutaneous reflex. One of the first cutaneous reflexes to be described was the cremasteric reflex by Romberg in 1853. Marshall Hall also described the grasp reflex at about the same time. Both Romberg and Hall recognised the value of eliciting these responses to aid the diagnosis of a number of conditions affecting the nervous system. In 1898 Babinski demonstrated the plantar reflex (Babinski, 1898). The reflex is evoked by firmly stroking the lateral side of the sole of the foot with a blunt object, causing flexion of the toe. Babinski further showed how a CNS lesion caused the toe to extend rather than flex, often known as Babinski sign.

The study of reflex responsiveness to cutaneous stimuli formed a major part of Sir Charles Sherrington's work. Performing experiments in the monkey, Sherrington first mapped the sensory and motor nerve root innervations in the latter half of the nineteenth century. He stimulated the end of the motor nerve root that had been severed close to the spinal cord, and observed which muscles contracted. From this he found that any one muscle is innervated by several segments of the spinal cord, although a single segment of the spinal cord can innervate a number of muscles. He then serially cut the posterior roots isolating the skin innervated by a single nerve root, finding that the distribution of sensory innervation was also segmental; the segmental sensory supply corresponded to the motor nerves and not the skin. There was a large amount of overlapping of the receptive fields of the sensory nerve roots innervating the muscle (Sherrington, 1896; 1897; 1898; 1900).

Once Sherrington had systematically revealed the pattern of sensory and motor root innervation, which he considered paramount in the understanding of the reflex response, he turned his attention to reflexes, and in 1910 he published a landmark paper containing the experimental findings obtained from studying a number of cutaneous reflexes in great detail (Sherrington, 1910). Using 'spinal' dog/cat preparations, he demonstrated flexion of the stimulated limb to painful cutaneous stimuli (Flexion reflex) and extension of the opposite limb when standing (crossed extension reflex). He also showed the extensor thrust of all limbs, evoked by applying pressure between the pads on the sole of the paw (extension reflex) and the rhythmical scratching motion of the hind limb (scratch reflex) observed in the 'spinal' dog days/weeks following section of the cervical spine, elicited by painful and non-painful stimuli applied to the skin covering the neck to the loin.

From these findings Sherrington found that reflexes were graded according to the characteristics of the stimulus eliciting the reflex response. Also he discovered that a reflex response could be inhibited, stimulation of the extensor muscles during the flexion reflex inhibited the reflex response (reciprocal inhibition); additionally he showed that reflexes exhibited fatigue and a rhythmical (refractory) nature (Sherrington, 1910; *Op. cit.* p37, Cohen, 1958).

Investigating the scratch reflex in the 'spinal' dog Sherrington found that some reflexes were *'allied'* in nature, when two separate areas of skin were stimulated individually no reflex response was elicited. However when both skin areas were stimulated simultaneously a reflex was evoked, Sherrington called these responses *'allied reflexes'*.

The extensive nature of Sherrington's work led him to establish many of the principles governing reflex integration. He suggested that muscles could receive a sensory as well as motor nerve supply from the same or distant spinal segments and connected pathways. He also suggested that in any one spinal segment that there could be a number of convergent reflex arcs all acting upon the same muscle/effector organ; that inputs from many reflex arcs converge by using a *'common path'* and that these inputs from could interact to produce greater or lesser responses depending upon their combination; regardless of this *'common path'* at the end of each reflex arc there was a *'final common pathway'* which was private to the muscle/ effector organ, which is the *'terminus ad quem'* of many reflex arcs generated by many receptive fields:

> " Reflex-arcs show, therefore, the general features that the initial neurone of each is a *private* path exclusively belonging to a single receptive point (or small group of points); and that finally the arcs embouch into a path leading to a path leading to an effector organ; and that their final path is common to all receptive points wheresoever they may lie in the body, so long as they have connexion with the effector organ in question. Before finally converging upon the motor neurone the arcs converge to some degree. Their private paths embouch upon *internuncial* paths common in various degree to groups of private paths. The teminal path may, to distinguish it from internuncial common paths, be called *' the final common path '*. The motor nerve to a muscle is a collection of such ' final common paths ' ".

From this work Sherrington believed that 'simple reflexes' represented the basic units required to produce movement, and that a complicated pattern of movement resulted from the combination of a number of 'simple reflexes' elicited by the stimulus. He considered this interaction vital for the control of movement. These findings were first published in 1906 in his book entitled *'Integrative action of the nervous system '*. These concepts have formed the basis of the current understanding of the reflex response since the early 1900's.

Continuing to carry out experiments until the early/mid twentieth century, Sherrington & Liddell, 1924 investigated 'reflex standing' which occurs in the 'decerebrate' cat preparation, showing that the posture adopted by placing the cat in the standing position stretches the extensor muscles producing a reflex contraction of the muscle that keeps the cat in the statue-like posture which prevents it from falling to the ground. Sherrington described this reflex as a 'postural stretch reflex', and also showed that 'reflex standing' was lost if the afferent supply to the extensor muscle was cut.

Later work by Sherrington and others demonstrated in animals that the pattern of the flexion reflex elicited by strong cutaneous stimuli could be reversed by altering the characteristics of the stimuli. The reversed reflex was thought to be due to overlap in the cutaneous receptive fields supplying both the flexion and extension reflexes (Creed *et al.* 1932).

In 1952, Hagbarth performed further experiments on 'spinal' and 'decerebrate' cats, which were designed to extend the original observations made by Sherrington (Sherrington, 1910; Creed *et al.* 1932). Hagbarth recorded the reflex response from the extensor muscles in the hind limb. He found that painful stimulation of large areas of the skin on the hind limb inhibited the extensor reflex, whilst stimulation of the skin overlying the extensor muscles had an excitatory effect. In contrast, he found the opposite effect when recording from the flexor muscles in the hind limb. Stimuli applied to large regions of the hind limb excited the flexor reflex except when the skin overlying the extensor muscle was stimulated.

Studies of cutaneous reflexes in man began by repeating the animal experiments that had been originally performed by Sherrington. Kugelberg *et al.* 1960, investigated reflex responsiveness to painful cutaneous stimulation in the lower limb of healthy subjects. The study showed that stimuli applied to the skin of the foot elicited a protective reflex flexion of the muscle, which caused the foot/limb to withdraw away from the painful stimuli in a similar fashion to the original animal experiments. He also showed that if the stimulus was applied to the limb whilst the subject was standing, the crossed- extension reflex could be elicited. Having established the existence of the flexion reflex in man, Hagbarth, based upon results described from Sherrington's original work, recorded the muscle activity from the extensor muscles in the lower limb of healthy adults. He applied painful cutaneous stimuli to different areas of the skin to see if it was possible to elicit an extensor reflex. He found that in healthy adults, stimulation of the skin elicited an extensor reflex response. He also found that the location of the cutaneous stimuli predetermined whether the extensor reflex was excited or inhibited (Hagbarth, 1960). Both Kugelberg *et al.* 1960 and Hagbarth, 1960 felt that these reflexes served a protective function in the lower limb.

The study of cutaneous reflexes to non-painful stimuli awaited the methodological advance that was developed by Upton, McComas & Caccia (Upton *et al.* 1971; Caccia *et al.* 1973). Firstly, they found that cutaneous reflex responses elicited by non-painful stimuli were only evident when the muscle was lightly contracting. Secondly, the size of the reflex response evoked by the stimulus was found to be so small that the EMG activity needed to be 'averaged' for the reflex response to be distinguished from the background EMG. Thirdly, it was found that the visualisation of the components of the cutaneous reflex response could be markedly improved if the EMG signal was rectified before averaging. The techniques employed to record reflex responses to non-painful cutaneous stimuli are described in detail in the following section.

## Methodologies employed to record a non-painful cutaneous reflex response

The earliest studies of cutaneous reflexes relied upon the visual observations of the reflex movements by the experimenter. The disadvantage of this method of recording was that it was qualitative, subjective and relied upon the experimenter to accurately relay the information. In response to these disadvantages, methods were developed that aimed to grade the strength or characteristic of different reflex responses in a more standardised fashion. Clinically, for example, the plantar reflex is either present or absent, it is then classified further as up going, mute or down going. Despite the limitations of this technique, it is still employed within the clinical environment today, often providing the clinician with valuable information regarding the nervous system.

For reflex responses to be studied in more detail quantitative recording techniques had to be developed. Initially mechanical devices were made to measure the reflex tension produced, the resultant tension was recorded using levers writing onto a rotating smoked drum and subsequently on an oscilloscope as technology developed. In this way quantitative measurements of reflex responses in terms of latency, amplitude and area could be made.

These techniques while adequate for the recording of large reflex responses were unable to record small cutaneous reflex responses, which produced little change in muscle tension. One approach which was employed to solve this problem was to superimpose several responses onto a photographic plate, the superimposed responses allowed the reflex response to be distinguished from the background noise more easily (Dawson & Scott, 1949). However, this technique was time consuming and difficult to perform. It was the revolutionary development of the ' averaging technique ' by George Dawson in 1951 that resolved these resolution problems and allowed the recording of extremely small responses in an EMG signal that were impossible or difficult to record prior to this development. The ' averaging technique ' is based upon the principle that any change in EMG signal generated in response to a stimulus is constantly related in time, and that it is a physically identifiable event thus allowing the recorded signal to be ' time locked ' to the stimuli. In this manner it is then possible to detect the response from other random signals not time locked to the stimulus. In averaging a specified number of stereotyped stimuli are delivered, and the response evoked by each stimulus is recorded for a given time period. Each response elicited by the successive stimuli is summed together and divided by the number of stimuli that have been delivered to give an overall averaged potential by the ' averager '. Thus averaging acts by increasing the ' signal to noise ' ratio; the size of the signal to noise ratio is increased by the square root of the number of stimuli given.

Cutaneous reflex responses elicited by non-painful stimuli are only seen as a modulating effect upon the EMG response in a muscle during a sustained low amplitude contraction. These responses are still difficult to distinguish even when ' averaged ' because the increases and decreases in the EMG are equally distributed about the baseline. It was not until 1970 that this problem was solved, when Gassel and Ott demonstrated how it was possible to improve the visualisation of these responses by passing the EMG signal through a full-wave rectifier before the ' averager '. Rectification works on 2 principles, the first is that if the EMG is rectified and averaged without the presence of the stimuli, the resultant average is a flat horizontal baseline and the second principle is that any vertical displacement above or below the baseline is proportional to the size of the muscle contraction. Therefore any excitatory effects of the motor neurones upon the muscle are registered as an increase in the level of the EMG and any inhibition as a reduction in the EMG level (Gassel & Ott, 1970). The relationship between the rectified baseline EMG and the size of the reflex response has been shown to be linearly related which means that the size of the reflex can be defined as a fraction of the baseline EMG (Deuschl *et al.* 1988).

The first recordings of cutaneous reflexes to electrical non-painful stimuli in man using rectification and averaging were made in the lower limb (Upton *et al.* 1971) and upper limb

(Caccia *et al.* 1973). In this way, Caccia *et al.* 1973 showed that non-painful electrical stimulation of the digital nerves of the index finger evoked a triphasic reflex response which Caccia *et al.* 1973 considered to be a reflection of differences in the conduction velocities of the afferents eliciting the reflex response; this started an investigation into the reflex pathways of the cutaneous reflex elicited by non painful stimuli in the upper limb, which has continued to the present day.

## Cutaneous reflexes recorded from the intrinsic hand muscles

The study of the reflex control of finger movement has proved to be fruitful in the investigation of the spinal and supraspinal reflex pathways. A major part of the research has centred on cutaneous reflexes recorded from the intrinsic hand muscles. These are described in the following sections.

Modest, non-painful electrical stimulation of the digital nerves of the index finger produces a reflex modulation of the ongoing muscle activity (EMG) recorded during a sustained voluntary contraction of the 1DI muscle (Jenner & Stephens, 1982). The cutaneous reflex, which is also called cutaneomuscular reflex (CMR) is typically triphasic in appearance; there is a initial increase of EMG, with onset latency at approximately 30ms (E1) followed by a decrease, at about 45ms, (I1), followed by a prominent second increase, (E2) with a longer latency of about 55ms (see Fig. 1). The size of each of the reflex components E1, I1, and E2 is expressed in terms of percentage modulation of background EMG (Nadler *et al.* 2000). An example of a typical reflex response is illustrated in Fig. 1.

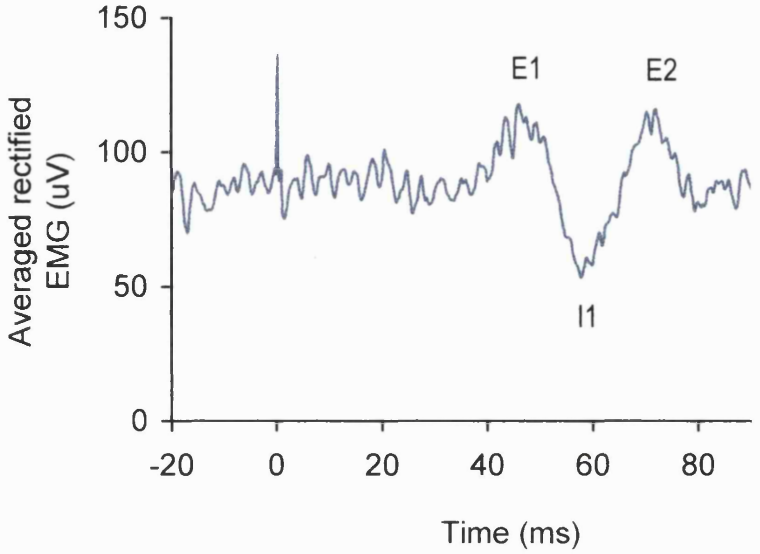


**Figure 1. Cutaneomuscular reflex**

A typical cutaneomuscular reflex recorded from the ID muscle at 10/20% of maximum following electrical stimulation of the digital nerves index finger. Stimulation 2.5 times above the level of sensory perception, 5s$^{-1}$. 250 sweeps.

There is a large body of evidence to suggest that each of the components of the CMR have different origins within the CNS. The E1 component is spinal in origin, whilst the I1 and E2 components are supraspinal in origin, requiring the integrity of the dorsal columns, sensory cortex, motor cortex and corticospinal tract. The evidence supporting this statement is described in the next section.

## Central nervous system origins of the cutaneous reflex

### *Short latency spinal pathways*

Hagbarth was one of the first people to provide evidence that the flexion reflex evoked by painful cutaneous stimuli had a short latency, which was compatible with the mediation of a reflex arc originating within the spinal cord of a cat (Hagbarth, 1952). The experiments were designed on the basis of the original observations made by Sherrington (Sherrington 1906,1910) in which, he obtained recordings from the extensor muscles in ' spinal cats '. He found that it was possible to evoke an extensor reflex from the skin overlying the extensor muscle, reflected in by changes in the ongoing muscle activity and tension at a short latency. From this finding Hagbarth concluded these findings provided evidence that the origins of the reflex were within the spinal cord. In later studies Hagbarth showed that the time it takes for the earliest phase of the reflex to be seen in the human lower limb muscles is too short to have an origin anywhere else except for within the spinal cord (Hagbarth, 1960).

Similarly, Jenner and Stephens, 1982 suggested a spinal origin for the E1 component of the CMR recorded from 1DI to stimulation of the digital nerves of the index finger on the grounds that the central delay for this component (ranging from 2-6ms) was insufficiently long to involve a transcortical pathway. Additionally, clinical evidence was provided from the studies of a patient with a neurological lesion affecting the motor cortex. In this patient the E1 component was preserved whilst the other components were abolished. Similarly the E1 component has been shown to be unaffected in patients with acute lacunar infarctions whilst the later components are reduced and delayed (Chen *et al.* 1998).

Further observations regarding the origin of the E1 component of the CMR have come from recent studies on patients with X-linked Kallman's syndrome. These patients have a novel fast conducting ipsilateral as well as contralateral cortico-spinal projection, as revealed by focal magnetic stimulation. Within this patient group there are also a small number who only have a largely single ipsilateral corticospinal projection. Following stimulation of the digital nerves in these individuals, whilst concurrently recording the CMR from the contralateral and ipsilateral 1DI muscles, the E1 component is only elicited from the1DI muscle ipsilateral to the stimulus whilst the later components are recorded only from the contralateral 1DI muscle (Mayston *et al.* 1997).

### *Long latency transcortical pathways*

The initial suggestion that some components of a reflex might reflect activities generated by supraspinal pathways were based upon human experiments by Hammond, in which he suddenly extended the elbow whilst simultaneously recording the ongoing muscle activity from the biceps. Hammond found that there was an initial burst of EMG at a short latency compatible with the spinally generated tendon jerk reflex. In addition he observed a second EMG burst which occurred at a much longer latency, and which appeared to be influenced by the subject (Hammond, 1960).

Later, Phillips using indirect evidence from studies on the primate also speculated that the stretch reflex might have a transcortical origin (Phillips & Porter, 1964; Phillips, 1969). At about the same time, Marsden & collegues used recordings of the flexor pollicis longus (FPL) muscle to show that sudden small random perturbations of the joint of the thumb tip evoked a reflex response that consisted of a series of waveforms, some of which were of too great a latency to be spinal. The long latency components were considered to have a supraspinal origin (Marsden *et al.* 1973).

It was not until 1972/3 that Evarts provided the first direct evidence of the pathway of the afferent input to the motor cortex. Using awaking monkeys he recorded the activities from the pyramidal tract neurones (PTNs) of during different movement tasks. He found that the PTNs responded very rapidly to a sudden peripheral change. The time interval of PTNs firing was such that it could indicate the use of a fast transcortical reflex pathway.

Marsden employed SEP's to measure the afferent conduction time to the cortex and back to the muscle by directly stimulating the motor cortex. It was found that the time taken was long enough for the long latency response to occur (Marsden *et al.* 1973; Lee & Tatton, 1975). Furthermore it was also noted that the central delay of the stretch reflex was greater when evoked from an arm muscle compared to a face muscle (Marsden *et al.* 1976).

Additional evidence arose from the studies of patients with neurological disorders and pathology affecting the CNS. It was found that lesions affecting the sensory columns and sensory-motor cortex delayed or abolished the long latency reflex component (Marsden *et al.* 1977; Lee & Tatton, 1978).

More recently, using magnetic stimulation to stimulate the motor cortex over a region corresponding the FPL muscle studies have shown that the sum of the facilitation produced by magnetic stimulation and the long latency reflex response evoked by sudden thumb extension is larger than when each response is evoked individually, providing further evidence that the long latency stretch reflex involves a transcortical pathway. This was not found to be the case for the short latency component of the stretch reflex, supporting evidence suggesting a spinal origin for this component (Day *et al.* 1991; Palmer & Ashby, 1992).

Similarly reflexes evoked by a non-painful cutaneous stimuli display a similar pattern of short and long latency components. Upton *et al.* 1971 recorded a reflex response in the leg and hand following mixed nerve stimulation. Two increases in EMG were recorded. The first corresponded to a spinal latency (V1) whilst the second longer latency reflex component (V2) occurred later at 50-60ms. Similarly Conrad & Aschoff, 1977 showed that the long latency components of the reflex response of the abductor pollicis brevis were delayed or absent in hemiplegic patients. It was suggested from these findings that this was evidence for the existence of a transcortical pathway.

Evidence that both I1 and E2 components of the CMR elicited from 1DI to digital nerve stimulation of the index finger are supraspinal in origin has come from a number of sources. Firstly in terms of the latency Jenner & Stephens, 1982 provided evidence that the E2 component was unlikely to be spinal in origin, instead suggesting that the E2 component was sufficiently long enough to involve a transcortical pathway. The latency of the I1 component was such that this could indicate a spinal or supraspinal origin.

Secondly, studies of patients with lesion of the motor cortex have revealed that both the I1 and E2 components of the CMR are abolished (Jenner & Stephens, 1982). This finding provides further supportive evidence that the E2 component could not have a simple spinal origin but was likely to involve a transcortical pathway. The reported abolition of the I1 component in such patients was less certain, on one hand this abolition could be used to provide evidence that the component could be supraspinal in origin, but on the other hand it was possible that the I1 component was simply spinal in origin, but was under the influence of the motor cortex.

Yet further clinical evidence to providing insight into the origins of the E2 component of the CMR was found by recording the reflex in patients with Klippel-Feil syndrome. Individuals with this syndrome exhibit mirror movements that are explained by the presence of abnormally branched corticospinal tract which project to motor neurone pool on both sides of the spinal cord. In these individuals if you concurrently record the CMR from both the contralateral and ipsilateral 1DI muscles, following unilateral stimulation the E2 component of the reflex is recorded from both the contralateral and ipsilateral 1DI muscles (Farmer *et al.* 1990).

A number of studies employing focal magnetic stimulation have investigated further the origin of the E2 and I1 components of the reflex. Some of the earliest work was performed by Palmer & Ashby, 1992 and Maertens de Noordhout *et al.* 1992, in both studies they magnetically stimulated the motor cortex at high intensities at a point in time when the E2 phase of the CMR component elicited by electrical stimulation of the digital nerves would naturally occur, so that both would occur concurrently, this was compared with the individual response obtained from magnetic stimulation alone. In both studies they reported that there was less facilitation of the MEP than the algebraic sum of the responses produced by stimulating individually, concluding that there was actually a decrease in the excitability of the motor cortex during the period of time that the E2 phase of the component would naturally occur. From these observations Maertens de Noordhout *et al.* 1992 suggested that the E2 component was not supraspinal, but was a spinal reflex that was subject to tonic facilitation from higher cortical regions.

In 1994 Ohki *et al.* provided contradictory evidence suggesting that the E2 component of the CMR was not spinal in origin but was supraspinal involving some kind of transcortical pathway. In this study they asked the question of whether the facilitatory effect upon the MEP reported previously was dependent upon the intensity of the magnetic stimulus. The experimental procedure was the same as that performed by Palmer & Ashby in 1992, but in this study the motor cortex was magnetically stimulated at both high and low intensities. It was found that at low intensities when the cortex was stimulated at the same time as the E2 phase of the CMR component that the algebraic sum of the MAP was larger than when comparing the sum of the response obtained during the magnetic stimuli alone. However when the procedure was repeated at high intensities little or no facilitatory effect was seen. It was suggested that at high intensity magnetic stimulation a large amount of inhibitory pathways are activated which masks the facilitatory effects seen in the cortex in association with E2 phase of the CMR component. From these findings it was concluded that this could be taken as evidence that the E2 component was supraspinal involving a transcortical pathway.

More recently, one of the strongest sources of evidence suggesting that the I1 and E2 components are mediated via a transcortical pathway has come from recordings obtained from subjects with X-linked Kallman's syndrome (Mayston *et al.* 1997). One of the features of the syndrome is pathological mirroring, explained by the presence of a novel fast conducting ipsilateral as well as a contralateral corticospinal projection identified by using focal magnetic brain stimulation. When the digital nerves of the index finger are stimulated in these individuals, the I1 and E2 components elicited from the muscle 1DI are not only seen ipsilateral, but also contralateral to the stimulated side, providing evidence for a transcortical pathway (Mayston *et al.* 1997). This provides yet further evidence that both the E2 component is supraspinal in origin, this is also appears to be the case for the I1 component.

In the last two years new evidence suggesting a supraspinal as opposed to a spinal origin for the I1 component has been provided in a study performed by Tokimura *et al.* 2000. Using focal magnetic stimulation it was shown that the cutaneous input evoked following electrical stimulation of the digital nerves of the finger / median nerve at the wrist resulted in a reduction in the excitation of the motor cortex at a short latency. It was suggested that this short latency suppression in cortical excitability occurs at the same time as the I1 phase of the CMR.

Although this evidence suggests that both the I1 and E2 components are supraspinal in origin it has become increasingly apparent that each component has different characteristics. In example, the E2 component of the reflex shows greater habituation to a stimulus than the I1 component (Harrison *et al.* 2000). It is possible to speculate that each of the components may have a different route of transcortical mediation.

In summary, it is generally accepted that current evidence suggests that the E1 is generated at a spinal level. The I1 component is supraspinal in origin, but appears to be different from the E2 component of the reflex. The E2 component is accepted as having supraspinal origin, involving a transcortical pathway that requires the integrity of the dorsal columns, motor cortex and corticospinal tract.

## The anatomical substrates for the cutaneous reflex

The afferent fibres of the digital nerves stimulated by the electrical stimulus evoking the cutaneous reflex response originate from low threshold mechanoreceptors in the glabrous skin of the finger. There are four identified types of low threshold mechanoreceptor in the human glabrous skin; fast adapting type I (FA I), and II (FAII) that end in Meissner corpuscles and Pacinian corpuscles respectively, and slow adapting type I (SAI) and II (SAII) that end in Merkel cells and Ruffini corpuscles respectively (Johnson, 2001). Studies of the human hand, have revealed that the innervation density of the FA I / SAI type mechanoreceptors are greatest in the fingertip with FAI (130 units/cm$^2$) predominating over SAI (80 units/cm$^2$). Looking at the innervation density in the finger, FAI and SAI mechanoreceptors are equally evident but the density is much lower compared to the tip of the finger. The FAII and SAII type mechanoreceptors are equally distributed throughout the finger and hand (Johansson & Vallbo, 1983).

The mechanoreceptors are also characterised according to their actions, FAI and SAI receptors have small discrete receptive fields. FAI responds to transient skin indentation, the receptor discharge is rapidly adapting whilst the SAI responds to sustained skin indentation, the receptor discharge is slowly adapting (Johansson & Vallbo, 1983). FAI mechanoreceptors are four times more sensitive and respond to stimuli over the whole of its receptive field unlike SAI type mechanoreceptors. It is considered that FAI mechanoreceptors play a role in the mediation of a neural image of skin motion whilst SAI type mechanoreceptors are involved in the mediation of a spatial neural image of the stimuli at a given moment in time (Johnson, 2001; Johnson *et al.* 2000). The FAII and SAII have characteristic receptive fields that are ill defined and large. FAII mechanoreceptor discharge is rapidly adapting they exhibit extreme sensitivity responding to high frequency transients stimuli. It is thought that these receptors are important in the transmission of vibration of the hand when in contact with an object. Finally SAII mechanoreceptors are slowly adapting responding to sustained skin indentation. They are about 6 times less sensitive to the indentation of the skin but they are 2-4 times more sensitive to the amount of skin stretch than SAI mechanoreceptors. It is therefore believed that these receptors convey neural information about the amount of skin stretch in the hand (Johnson, 2001).

Deuschl *et al.* 1995 showed that following stimulation using air puff stimuli applied to the tip of the finger which were designed to stimulate the mechanoreceptors, elicited a cutaneous reflex response which consisted of a short latency increase in the EMG followed by a decrease and then by a second long latency increase. From these observations they suggested that the short latency component had spinal origins whilst the long latency component supraspinal origins. Deuschl *et al.* also showed that the relationship to the cutaneous reflex evoked by electrical stimulation of the digital nerves and the air puff stimuli were comparable except that the responses evoked by air puff stimulation were 2-3ms longer in latency than the responses evoked by stimulation of the digits. In addition they showed that a local anaesthetic block applied to the cutaneous nerve branches abolished the reflex response. These findings provided supportive evidence that only cutaneous receptors and their respective afferents were involved in generating the reflex response elicited by both the electrical and air puff stimuli.

New evidence suggests that all four types of low threshold mechanoreceptor are excited by the natural air puff stimuli (Mizobuchi *et al.* 2000) evoking the cutaneous reflex response. Similar findings are found when comparing the SNAP evoked by natural tactile stimuli with the SNAP evoked by electrical stimulation (Caruso *et al.* 1994). It is therefore likely that the afferent fibres of the digital nerves of a finger originate from all four cutaneous low threshold mechanoreceptors. However, it may not necessarily be the case that all four types of mechanoreceptor have a modulating effect upon the EMG. Recent findings suggest that the input from single FAI, FAII & SAII afferents have a modulatory effect upon the EMG, but SAI, muscle spindles & joint afferents do not have the same modulating effect (McNulty *et al.* 1999; McNulty & Macefield, 2001).

The afferent fibres are most likely to be transmitted utilising the fast conducting II or Aβ class fibres given the conduction times involved in the generation of the reflex (Garnett, 1979; Jenner & Stephens, 1982).

The existence of a pathway from cutaneous afferents to the M1 has been demonstrated in a number of experiments. Initial studies using primates showed that neurones within M1 were responsive to natural cutaneous stimuli (Rosén & Asanuma, 1972; Lemon & Porter, 1976).

In 1973 Evarts provided evidence of the existence of a direct fast conducting pathway from cutaneous afferents to M1 in the monkey. Recording the activities of the PTNs during a range of movement tasks, He found that sudden perturbations of a joint or stretch of a muscle during a movement task produced a very rapid firing of the PTNs. From these observations Evarts suggested that the timing of the PTNs could indicate the transmission of the afferent information via a fast conducting transcortical reflex pathway (Evarts, 1973). Furthering these observations Lemon, 1979 measured this fast pathway finding that the response of the PTNs to the stimuli applied to the fingers and hand were particularly rapid occurring about 7-8ms after the stimuli in the monkey (Lemon, 1979).

Brinkman *et al.* 1978 showed that if the dorsal columns were sectioned, the input to M1 and PTNs response were lost. This led the authors to suggest that the dorsal columns were the route by which afferent information was conveyed to the cortex.

Later recordings showed that cutaneous afferents projected to the caudal and proproceptive afferents to the rostral regions of M1 with some intermingling at the border. The zones of the afferent inputs in M1 were found to be small and restricted to a single digit; there are a few neurones in M1 that respond to both cutaneous and proprioceptive afferent information (Lemon, 1981*a*; Picard & Smith, 1992).

Lemon has also shown that there is a relationship between cutaneous afferent information and the response of the M1 neurones. He showed that during a finger movement task (performed by a monkey) the M1 neurones were more active in tasks that involved small precise finger movements compared to grasping or pulling. He found that there was an increase in the neurone discharge just before hand contact, and also reported very high firing frequencies during exploratory movement (Lemon, 1981*b*)

The efferent limb of the pathway evoking the reflex is most likely to be mediated by fast conducting α motor neurones. Evidence for this comes from work by Jenner, in which it was found that the central delay for the E1 component of the reflex recorded from 1DI following index finger digital nerve stimulation was only 2.4 - 6.2ms, meaning that only a few interneurones could be involved in the pathway if 1ms is allowed for each synapse and spinal interneurone (Jenner, 1981). Evidence for a direct monosynaptic efferent corticomotoneuronal (CM) pathway from M1 to the α motor neurones to the muscles has been shown in monkeys (Kuypers, 1964). Using magnetic stimulation to stimulate the M1 it has been shown that the highest proportion of CM cells project to the more distal muscles of the hand; the amount of CM projection appears to correlate with the amount of dexterity of the fingers; sectioning of the descending pyramidal tract abolishes the response generated in the muscle (Lemon, 1995).

It has been shown that electrical stimulation of the M1 evokes short latency muscle activity (Rosén & Asanuma, 1972). The same also occurs if the supplementary motor cortex (SMA) (Mitz & Wise, 1987), or premotor area (PMA) (Weinrich & Wise, 1982) is stimulated. The early studies by Penfield using the preceding technique showed that the motor cortex was organised into body regions with specific regions being dedicated to the movement of that body part. However the internal organisation within a given body region is not organised in a somatotopic fashion instead there are multiple representations of neurones responsive to individual muscles and they also overlap each other considerably (Donoghue & Sanes, 1994).

The M1 receives a dense corticocortical projection from S1. The S1 is the centre where afferent information arrives within the cortex. Cutaneous inputs are relayed to area 3b and proprioceptive inputs to area 3a. Further processing of the afferent information is carried out within area 1 (cutaneous input) and area 2 (priopceptive input). Area 6, 8 & supplementary motor area (SMA), collectively known as the pre-motor cortex (PMA) located in the frontal lobe also send sensory input to the M1. The PMA receives inputs from the prefrontal association cortex (45 & 46) and parietal association cortex (5 - 7). The M1 also receives afferent input from the ventrolateral regions of the thalamus. In addition the M1 is influenced by wide spread aminergic systems that originate from the brainstem (Donoghue & Sanes, 1994).

The existence of such neural substrates has led to the suggestion that the cutaneous reflex is mediated via a fast conducting transcortical pathway in which afferent information generated from mechanoreceptors & afferents is relayed via the dorsal columns to S1 where it is relayed to M1 via a corticocortical projection, and then relayed back to the muscles via CM neurones within the pyramidal tract.

In the present thesis recordings of the cortical somatosensory evoked potential (SEP) following electrical stimulation of the digital nerves of the index finger were employed to examine the afferent pathways. The following sections describe the recording technique.

## Cortical somatosensory evoked potentials

George Dawson (1950) recorded the first SEP elicited in response to the electrical stimulation of the large diameter afferent fibres in a mixed peripheral nerve. Since this original observation many further studies have confirmed the presence of and have investigated the origins of the components of the SEP (Giblin, 1964; Allison *et al.* 1980; Lesser *et al.* 1981).

The cortical SEP is recorded from electrodes attached to the scalp overlying the contralateral sensory cortex (S1). The electrodes are positioned according to the International 10-20 system (Jasper, 1958; Homan *et al.*1987). The 10-20 system is a standardised method of measurement for the placement of electrodes on the scalp according to their anatomical location; the electrodes are placed at distances 10 and 20 percent from each other.  The S1 is located 70mm lateral to a mark 25mm behind the vertex (usually denoted C3', International 10-20 System). The vertex (denoted Cz, International 10-20 System) is found by measuring 50% from the nasion to the inion, and 50% from one pre-auricular point to the other so that both measurements bisect to from a cross locating the vertex.

The recording electrode is linked to a reference electrode. The position of the reference electrode can vary. Ideally the reference electrode should be situated at a site that is ' indifferent ' to the stimulus. It is often difficult to truly assess the effect of the potentials evoked at the reference site because they can only be measured as a potential difference relative to some other location on the body. In the present study two different reference positions were used. The first was a cephalic reference located on the scalp at a distance located at 30% of the distance between the nasion and the inion in the midline of the scalp (denoted Fz by the International 10-20 System). This site is routinely used in the clinical environment, and has the advantage that it is often easy to record the early cortical components of the SEP because there is little in the way of muscle and ECG artefacts, and is recommended by the IFCN as the site to use when recording the cortical SEP (Nuwer *et al.* 1994). Conversely the reference has the disadvantage that it is influenced by frontally generated cortical components. Desmedt & Tomberg, 1989 have shown that although the cortical components labelled P20 and N30 of the SEP are influenced by frontally generated early components from the reference site, it does not appear to greatly influence the N20 or P25/27 components of the SEP. A second non-cephalic earlobe reference electrode attached ipsilaterally to the site of stimulation was employed as the alternative reference electrode in the present thesis. This site has the advantage that it is not influenced by the components generated by the cortex, and placing the electrode ipsilaterally records larger potential differences than a reference electrode placed contralateral to the site of stimulation and so makes the cortical SEP easier to record (Tomberg *et al.* 1991). However this site is prone to contamination from ECG and EMG related artefacts, often resulting in a reduction in the clarity of the recording, which is an important factor when recording very small potentials. In the present thesis only the N20/P25 components of the SEP were investigated, and wherever possible a non-cephalic ipsilateral earlobe reference has been used in preference to the cephalic Fz reference to record the SEP.

The electrical stimulus used to elicit the SEP is usually presented at a frequency of 2-5Hz for 0.1ms. The intensity of stimulation will vary with each individual but as a rule 2.5 times above the threshold of sensory perception is usually used. Stimulation of the nerve at these intensities will activate the large myelinated group I and group II afferent fibres, because they are easily excited at these levels (Jones, 1993). One disadvantage with this type of stimulus is that it does not allow a distinction to be made between the different receptors types and their respective sensory modalities of touch and vibration, all of which are carried by large diameter myelinated afferent fibres with in the digital nerve. Stimulation of a mixed nerve such as the median nerve presents with the additional problem that some of the afferent information will be generated by muscle afferents, however Halonen *et al.* 1988 have shown that information derived from muscle afferents make less than a 10 percent contribution to the cortical SEP evoked in response to stimulation of the median nerve. This finding shows a good correlation with cross-section sampling of the afferents of the median nerve showing that less than 6 percent of the fibres were occupied by muscle fascicles (Sunderland & Bedbrook, 1949).

Electrically stimulating a mixed nerve at the wrist evokes a response that consists of a series of positive and negative waveforms, extending over 200ms in duration. The response can be recorded from surface electrodes attached to the skin from any point along the somatosensory pathway. In the clinical environment recordings are typically made from the clavicle, cervical, and cortical regions. The waveforms evoked in the first 30ms are defined as the short-latency components, whilst waveforms recorded from 30ms onwards are termed middle or late SEP components. Each waveform is also labelled in terms of the polarity and latency.

Electrical stimulation of the digital nerves of a finger evokes a similar series of waveforms, but the SEP to digital nerve stimulation is smaller than the mixed nerve evoked response and often requires more averages when compared to mixed nerve stimulation (Desmedt & Cheron, 1980; Synek, 1986). The waveforms are longer in latency because the peripheral conduction distance is longer. Typically the latency is increased by 3-5ms but often each component is identified by the same label as the SEP components evoked by mixed nerve stimulation to avoid confusion. Figure 2 shows a typical averaged cortical SEP evoked by stimulating the digital nerves of the index finger. Approximately 20msec after the electrical stimulus a number of near field potentials each with a distinct generator are recorded from the scalp electrode overlying the sensory cortex. From the Fig.2 it can be seen that there is an initial negative rise in the averaged ongoing EEG, the N20 SEP component, followed by a decrease, the P25 SEP component. This component often merges with the P30 component to give a later P27 component (Jones, 1993). Each component is measured in terms of peak-to-peak amplitude, or peak amplitude.

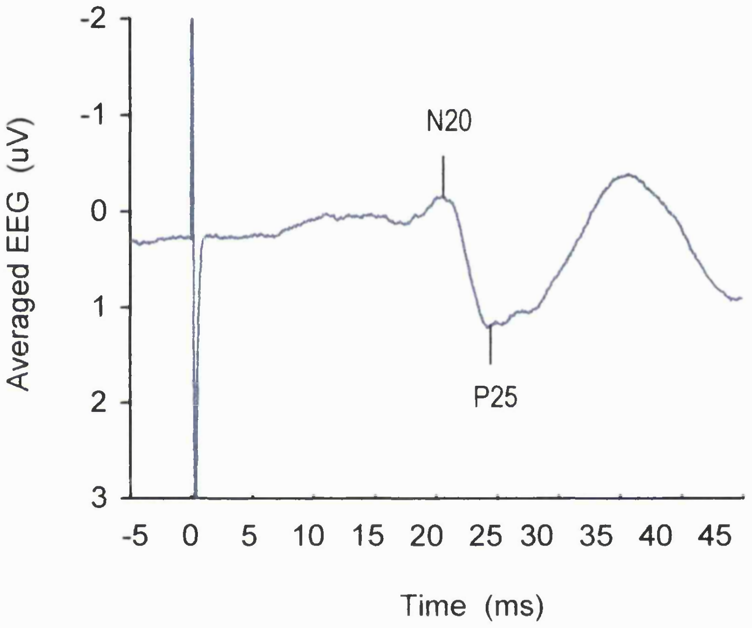


**Figure 2. Digital somatosensory evoked potential**

Typical recording of the digital nerve SEP recorded from an electrode attached to the scalp over the contralateral S1 following stimulation of the digital nerves of the index finger 2.5 times above the level of perception. 5s$^{-1}$. 2560 sweeps.

## The anatomical organisation of the somatosensory cortex

Afferent information from the thalamus is relayed to S1which is divided into 4 distinct cytoarchitectonic regions labelled area 3a 3 b, 1 & 2. Each of the four regions contains a complete map of the body surface (Nelson *et al.* 1980). The majority of afferent fibres from the body terminate in either 3a, which is concerned with afferent information arising from deep tissue/stretch receptors or 3b, which is concerned with afferent information from slow and rapidly adapting mechanoreceptors arising from the skin. Neurones in area 3a & b send a small direct corticocortical projection to areas 2 which receives inputs from a mixture of modalities, rapidly and slowly adapting cutaneous receptors and proprioceptors and area 1 which receives a high proportion of inputs derived from rapidly adapting cutaneous mechanoreceptors respectively (Jones & Friedman, 1982). The afferent inputs appear to be organised in a column fashion and characterised by the receptive field and sensory modality. The cortex in this region is divided into 6 layers. Layers I, II & III send 'projections' to areas 1,2 & SMA. Layer IV receives input from the thalamus, layer V sends a 'projection' to the basal ganglia, brain stem & spinal cord, and the last layer VI sends a 'projection' to the thalamus (Sur *et al.* 1984). As with the motor cortex there is no internal somatotopy of the neurones and there are multiple sensory representations (Iwamura *et al.* 1985; Biermann *et al.* 1998).

## Central nervous system origins of the SEP

The N20/P25 SEP components recorded from electrodes attached to the scalp over the contralateral sensory cortex are thought to reflect cortically generated activities within the S1. Current evidence suggests that the N20 component represents afferent activity arriving at

Brodmann's 3b area. The P25/7component is believed to reflect further processing of the afferent activities at Brodmann's area 1.

Goff *et al.* in 1962 provided the first detailed description of the N20 SEP component, in which he described as a widely distributed negative potential over the parietal regions of the head. Later, Broughton (1967) hypothesised that this component represented the primary response of the cortex. Evidence to support this hypothesis has arisen from direct recordings from the cortex in the monkey & human. Intracranial recordings in man have shown that there is a positive potential with a latency of about 20ms that is distributed over the pre-central gyrus of the cerebral cortex and a negative potential of similar latency over the post-central gyrus, compatible with a neural generator in area 3b of S1. A few milliseconds later a positive component peaking at 25ms is seen from the cortex to the central sulcus, compatible with a neural generator in area 1 of S1. Comparative findings are seen in monkey studies (Allison *et al.* 1980; Wood *et al.* 1988; Allison *et al.* 1991*a*).

There is also evidence of the generators of the N20 and P25 SEP components from studies on patients with lesions. Studies of the SEP following removal of the somatosensory cortex have shown that the N20 and subsequent components are abolished (Slimp *et al.*1986; Allison *et al.* 1991*b*).

Magnetoencephalography (MEG) is another method for examining the generators of the cortical components of the SEP. It has very good spatial and temporal resolution, because it is particularly good for detecting tangential currents to the skull; unlike the SEP in which the resolution is severely affected by volume conducted currents. Stimulation of the median nerve or digital nerves whilst recording from S1 using MEG produces a series of magnetic fields, the first negative field occurs at 20ms (N20 or 1M), followed by a positive field at 30ms (P30 or

2M). Subsequent waves occur at 40 (N40 or 3M), 60 (P60 or 4M) & 90ms (N90) (Kakigi *et al.* 2000; Xiang *et al.* 1997). Using this technique authors have shown that the N20 field corresponds to the N20 SEP component, both indicating a neural generator in area 3b of S1. The P25 component of the SEP is thought to equate to the P30 MEG field, both indicating a neural generator in area 1 of S1 (Huttunen *et al.* 1987; Jousmaki & Hari, 1999).

This section has aimed to review the background to the electrophysiological responses recorded in the present thesis. The following sections in part A of this thesis report the findings a series of experiments designed to examine reflex integration of the cutaneous reflex during different movement tasks.

# PART A: Sensori-motor integration during different finger movements in man

# Section 1: Active and passive finger movement is associated with attenuated cutaneomuscular reflexes recorded from the first dorsal interosseous muscle in man

## Summary

1. Cutaneomuscular reflexes, SEP's and the SNAP have been recorded during different types of finger movement tasks in man. With ethical approval and informed consent surface EMG recordings were obtained from the first dorsal interosseous muscle of the preferred hand, SEP's were recorded from the contralateral sensory cortex and the SNAP was recorded from the median nerve of healthy adult subjects whilst electrically stimulating the digital nerves of the index finger.

2. Three experiments were performed. In the first experiment, 15 subjects carried out the following tasks (*a*) a sustained abduction of the index finger against resistance at 10-20% MVC, and (*b*) abduction of the index finger as in (*a*) whilst performing self paced low amplitude tapping of the (i) index finger, (ii) thumb, (iii) middle finger, (iv) little finger. In the second experiment 4 subjects performed an abduction of index finger (a) as per the previous experiment and (b) abduction of the index finger as in (a) whilst tapping the ipsilateral foot. In the third experiment, 5 subjects performed an abduction of the index finger as in (a) whilst the middle finger was (i) actively tapped up and down by the subject in the same manner as the first experiment, (ii) passively moved up and down by the experimenter in a manner mimicking active finger tapping. The movements were low amplitude and self paced by the experimenter. Each task was presented at random and performed on two occasions in all experiments.

3. The E2 CMR and N20/P25 SEP components were significantly reduced during active finger tapping ($P < 0.05$ on each case).

4. There was a significant (qualitative) relationship between the decrease in the size of the E2 component of the CMR and the N20/P25 components of the SEP during active finger tapping (Chi-square, $P < 0.05$).

5. The reduction in the size of the E2 CMR and N20/P25 SEP component was independent of which finger was actively tapping ($P > 0.05$).

6. There were no significant changes in the size of the E1 and I1 components of the CMR during active finger tapping ($P > 0.05$), and the size of the SNAP was independent of task ($P > 0.05$ in each case).

7. The size of the E1, I1, E2 components of the CMR, and the N20/P25 components of the SEP were unaltered during foot tapping ($P > 0.05$).

8. Passive middle finger movement produced a 50.5% decrease in the size of the E2 CMR component and a 33% decrease in the size of the N20/P25 and 55% decrease in the size of the N20 SEP components. The size of the E2 CMR and N20/P25 and N20 SEP components were significantly reduced during passive middle finger tapping ($P < 0.05$).

9. Similar changes were found during concomitant active middle finger tapping, producing a 49% decrease in the size of the E2 CMR component and a 32% decrease in the size of the N20/P25 and 58% decrease in the size of the N20 components of the SEP. There was a significant reduction in the size of each of the E2 CMR and N20/P25 SEP components ($P < 0.05$).

10. No significant differences were found between active and passive middle finger tapping (*P* >0.05 in each case).

11. Passive middle finger tapping did not produce significant changes in the size of the E1, I1 CMR or P25 SEP components and the size of the SNAP and background EMG were unaltered (*P* >0.05).

12. Firstly, it is concluded that the decrease in size of the E2 CMR component associated with passive and active finger tapping results from gating of the digital nerve input and secondly it is concluded that sensory feedback from the periphery contributes to the process by which the digital nerve input is 'gated'.

## Introduction

The reflex effects of cutaneous stimulation on a given muscle are known to depend upon the task being carried out when the reflex is elicited. In the first dorsal interosseous muscle for example, the transcortical E2 component of the CMR evoked by stimulating the digital nerves of the index finger is greater when the subject performs a isolated finger abduction than when the muscle is active during the combined movement of all of the fingers, as in a power grip (Evans *et al.* 1989).

It is well established that cutaneous afferent input to the S1 is attenuated or 'gated' during both active and passive movement (Giblin, 1964; Rushton *et al.* 1981; Cheron *et al.* 2000). In man SEP recordings obtained directly from exposed cortex and the scalp have been used to provide evidence that the largest amount of 'gating' occurs at a cortical level (Cheron & Borenstein, 1987; Hsieh *et al.* 1995), whilst the least amount of 'gating' occurs at brainstem level (Hsieh *et al.* 1995).

Current evidence suggests there are a number of mechanisms by which 'gating' of afferent information occurs during a voluntary movement. Firstly corollary discharges to other motor regions generated in response to the voluntary movement have been shown to 'gate' the afferent information (Paus *et al.* 1996). More recently sensory feedback from the periphery (Cheyne *et al.* 1997) has also been shown to 'gate' the afferent information during a voluntary movement. It has been suggested that during passive finger movement that there are no corollary discharges, leaving only the afferent information from the sensory feedback generated from the periphery (Cheyne *et al.* 1997).

With this background in mind, the first and second experiments in the present study were designed to investigate the effect of performing concurrent small phasic active movements of a finger upon the size of the CMR recorded from the 1DI evoked by electrical stimulation of the digital nerves of the index finger during a sustained voluntary contraction of 1DI at 10-20% of MVC, whilst simultaneously recording the SEP from the contralateral sensory cortex. It is hypothesised that when finger tapping is performed whilst simultaneously abducting the index finger that the afferent information produced by the electrical stimulation of the digital nerves of the index finger will be 'gated' by the cortex and/or brainstem in favour of the afferent information generated by finger tapping. This 'gating' effect upon the afferent information produced by electrical stimulation of the index finger digital nerves would in turn result in a change in sensori-motor interaction, reflected by a decrease in the size of the CMR and SEP.

The third experiment was designed to examine the effect of active and passive middle finger movement upon the CMR recorded from 1DI during a sustained voluntary contraction of 1DI at 10-20% MVC, whilst concurrently recording the SEP from the contralateral S1 following digital nerve stimulation of the index finger. It is surmised that if afferent information generated from mechanoreceptor and proprioceptor activation in the periphery elicited during passive middle finger movement is involved in the 'gating' process then this information will be considered more relevant by the CNS than the afferent information generated by electrically stimulating the index finger. As a result the CNS will attend to the afferent information generated from the passive middle finger movement 'gating' out the index finger afferent information elicited by the electrical stimulus, reflected as in a decrease in the size of the CMR and SEP. It is also hypothesised that the magnitude of the 'gating' effect will be similar for active and passive middle finger tapping.

## Methods

### *Subjects*

Cutaneomuscular reflexes, digital nerve somatosensory evoked potentials, and sensory nerve action potentials were recorded from the preferred hand of 15 healthy subjects, aged 17-49 years (6 female) in experiment 1, from 4 subjects, aged 21-49 years (2 female) in experiment 2 and from 5 subjects, aged 24-37 (3 female) in experiment 3. All subjects gave informed consent. The experimental protocols were approved by the local ethics committee, and were in accordance with the guidelines set out in the Declaration of Helsinki, 1964.

### *Cutaneomuscular reflexes*

Reflexes were recorded from the first dorsal interosseous muscle. The surface EMG was recorded using self-adhesive electrodes that were placed on the skin over the belly of the muscle, inter-electrode distance 2.5cm. The subject was asked to abduct the index finger against resistance at 10-20% maximal voluntary contraction (MVC) using an LED root mean square voltmeter as a visual aid. The EMG was amplified, filtered (20Hz-5KHz) and stored on magnetic tape for future analysis.

### *Digital nerve somatosensory evoked potentials*

Recordings were made from the sensory cortex contralateral to the side of stimulation. The scalp was prepared using skinpure abrasive paste. Stick-on silver/silver chloride disk electrodes were placed onto the scalp using an adhesive conductive EEG paste. The active electrode was positioned 2.5cm behind Cz (International 10-20 System) and 7cm laterally. A reference electrode was placed onto the earlobe ipsilateral to the side of stimulation (Tomberg *et al.* 1991). The ongoing EEG was amplified, filtered (20Hz-2KHz) and stored on magnetic tape for further analysis.

### *Sensory nerve action potentials*

Sensory nerve action potentials were recorded using surface electrodes placed onto the skin overlying the median nerve at the wrist. The SNAP was amplified (20Hz-2KHz), and stored on magnetic tape for analysis.

### *Digital nerve stimulation*

The digital nerves of the index finger were electrically stimulated using ring electrodes, which were placed either side of the proximal interphalangeal joint. The stimulus was delivered using a constant current stimulator (Sapphire 4ME) at a level 2.5 times above that required for perception (pulse duration 100µs, frequency 5Hz). The perception threshold was determined while the subject's hand was relaxed.

### *Experiment 1*

Cutaneomuscular reflexes, digital nerve somatosensory evoked potentials, and sensory nerve action potentials were recorded, following digital nerve stimulation of the index finger. Subjects performed the following finger movement tasks: (a) a sustained voluntary abduction of the index finger at 10-20% MVC using a LED voltmeter as visual feedback, and (b) abduction of the index finger as in (a) whilst simultaneously performing concurrent small self paced tapping of the i) index finger, ii) thumb, iii) middle finger and iv) little finger. For each experimental run, subjects were asked to maintain the LED voltmeter monitoring 1DI EMG lit to the 10-20% MVC level. Once achieved, subjects were instructed to make small concurrent tapping movements of the finger throughout the period of digital nerve stimulation. The experimenter carefully monitored the subject and LED voltmeter EMG levels to ensure that the subject continued to abduct whilst performing the movement task. All subjects performed the finger movement tasks twice, and in a random order. Subjects rested for a few minutes between each task. Data were excluded if the subject was unable to perform the task, or produced a large amount of wrist movement making it impossible to record the afferent volley at the wrist.

*Experiment 2*

Cutaneomuscular reflexes, digital nerve somatosensory evoked potentials, and sensory nerve action potentials were recorded, following digital nerve stimulation of the index finger. In the second experiment four subjects from experiment 1 performed (a) index finger abduction as described in experiment 1(a) and (b) index finger abduction as per (a) whilst simultaneously performing self-paced tapping of the ipsilateral foot. Each subject performed (a) index finger abduction and (b) ipsilateral foot tapping twice, and in a random order. As with experiment 1 data were excluded if the subject was unable to perform the task, or produced a large amount of wrist movement.

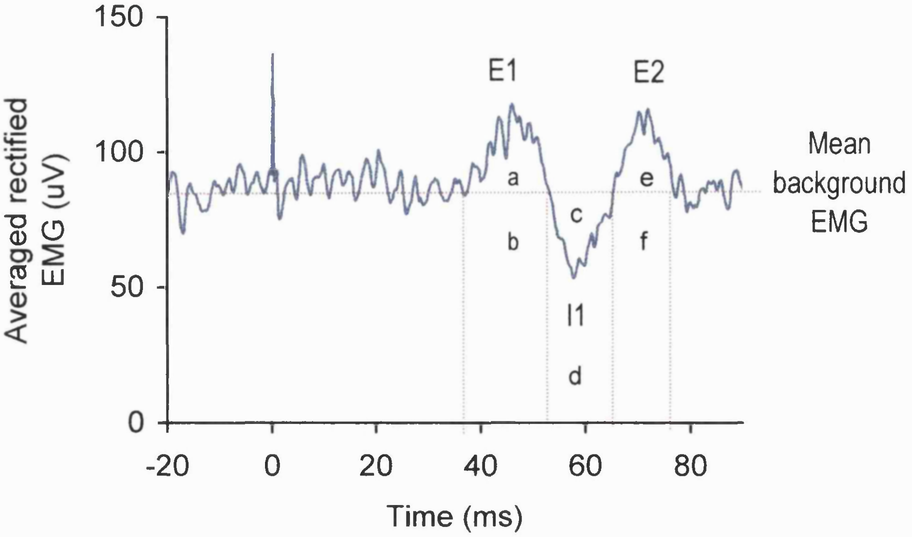
*Experiment 3*

In experiment 3, Cutaneomuscular reflexes, digital nerve somatosensory evoked potentials, and sensory nerve action potentials were recorded, following digital nerve stimulation of the index finger. In this experiment, 5 subjects performed (a) a sustained abduction of the index finger at 10-20% MVC as described in experiment 1, (b) index finger abduction as (a) whilst concurrently performing self paced low amplitude active tapping of the middle finger (as per experiment 1b(iii)) and (c) index finger abduction as per (a) whilst the experimenter concomitantly passively moved the middle finger up and down in a manner mimicking active finger tapping. In the case of passive middle finger movement experimental run, subjects maintained the 1DI EMG level lit to 10-20% MVC. As soon as this was achieved the experimenter moved the middle finger up and down in a manner mimicking active finger tapping using a lever, which was attached to the middle finger by a cord that could be pulled to raise the finger and released to lower the finger. The tapping was self-paced by the experimenter & low amplitude. The subjects were instructed not to resist the finger movement or to stiffen the finger, and they could not see their hand. The background EMG was monitored to ensure that there was no change in the EMG during passive movement. The tasks were performed twice and at random. Data were excluded as per experiment 1.

### *Analysis*

#### *Cutaneomuscular reflexes*

The amplified & filtered EMG signal was rectified and then averaged time-locked to the stimulus for 250 sweeps using the SigAvg program. The size of each of the reflex components E1, I1, and E2 was expressed in terms of percentage modulation of background EMG (Nadler *et al.* 2000). A component was considered present if it rose above or fell below the 95% confidence level of the mean EMG for at least 8ms (Wohlert, 1996). The enclosed area (µVms) of each component rising above or falling below the mean EMG level E1 (a), I1 (c) & E2 (e) is expressed as a percentage of the mean background EMG to zero area (µVms) of the enclosed component, E1 (b), I1 (d) and E2 (f). Hence the E1 % EMG modulation is (a/b) * 100, the I1 % EMG modulation is (c/(c + d)) * 100 and the E2 % EMG modulation is (e/f) * 100. The mean level of ongoing background EMG is found from a 20ms pre-stimulus period of EMG. This is illustrated in Fig.3. Because each finger movement task was performed twice in the same recording session, the mean percentage modulation was calculated for each component from the two recordings by taking the percentage modulation measured for each of the 250 sweeps. This was performed for each finger movement task in all subjects.



E1 % EMG Modulation = (a/b) * 100.
I1 % EMG Modulation = (c/ (c+d)) * 100.
E2 % EMG Modulation = (e/f) * 100.

**Figure 3. Measuring the size of the components of the cutaneomuscular reflex**

Shows a typical cutaneomuscular reflex recorded from the ID muscle at 10/20% of maximum following electrical stimulation of the digital nerves index finger. 250 sweeps.

*Digital nerve somatosensory evoked potentials*

The ongoing amplified & filtered EEG signal was averaged time-locked to the stimulus for 250 sweeps. The size of the SEP recorded following electrical stimulation of the digital nerves is particularly small. To improve the signal to noise ratio the two 250 sweep averages were combined using the SigAvg program to give a single 500 sweep average for each finger movement task. Each component was measured in terms of peak-to-peak amplitude, or peak amplitude. Using Fig. 4 as an example, the peak-to-peak amplitude of the N20/P25 components of the SEP was found by measuring from the peak of the waveform SEP component labelled N20 to the trough of the SEP component labelled P25. The peak amplitude was found by 'eyeballing' the averaged ongoing EEG over a 20ms pre stimulus period, drawing a mean line (shown as the dashed line on Fig.4) and then measuring from the mean averaged EEG to the peak of the N20 SEP component or from the mean averaged EEG to the trough for the P25 SEP component.

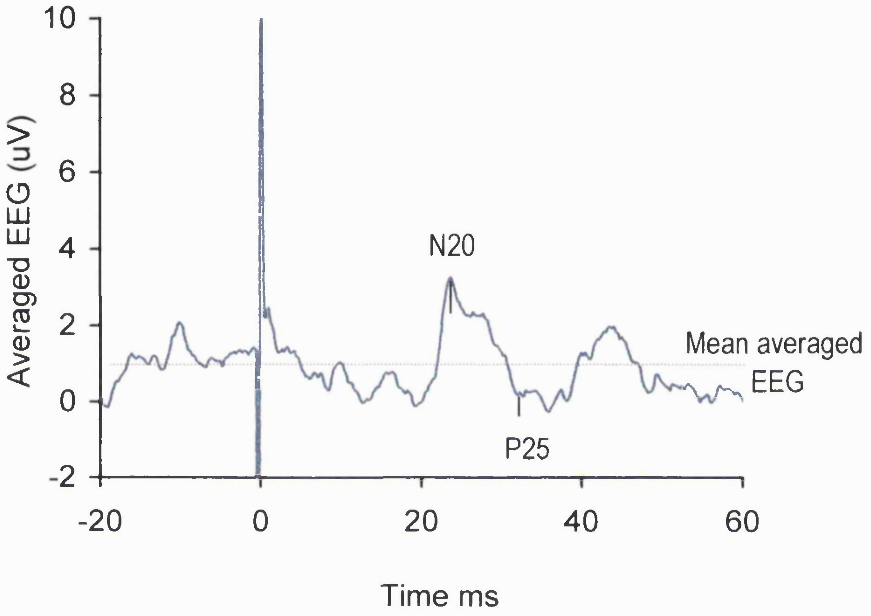


**Figure 4. Measuring the size of the components of the digital nerve somatosensory evoked potential**

Typical recording of the digital nerve SEP recorded from an electrode attached to the scalp over the contralateral S1 following stimulation of the digital nerves of the index finger. 250 sweeps.

*Sensory nerve action potentials*

The amplified and filtered signal was averaged time-locked to the stimulus for 250 sweeps (SigAvg program). The size of the SNAP was found by measuring the peak-to-peak amplitude.

*Statistical analysis*

The normality of the data distribution was established by visually assessing the frequency plots of the data and by performing the Kolmogorov-Smirov goodness of fit test (KS). The effect of finger tapping on the size of the CMR, SEP, and SNAP was examined by performing repeated measures analysis of variance (rmANOVA). The Chi-square test for association with Yates continuity correction was also employed. Any significant association was further verified by employing Fishers exact method. The level of statistical significance was set at $P < 0.05$.

## Results

### *Experiment 1 & 2: Effect of finger and foot tapping*

Fig. 5 shows the effect of simultaneously making a finger movement on the averaged rectified EMG recorded from 1DI during a sustained voluntary abduction of the index finger for one subject. During simple index finger abduction (Fig. 5*A*) without simultaneous finger tapping, the stimulus clearly elicits three components; a short latency increase in EMG, E1 followed by a decrease, I1 followed by a second increase, E2 producing percent EMG modulations of 15.5, 19.2 & 19.5 respectively. In contrast, when this subject performs self-paced tapping of the index finger whilst simultaneously abducting the index finger, there is a clear reduction in the size of the E2 modulation, decreasing from 19.5 to 6.1. The E1 and I1 modulations are unaltered producing percent EMG modulations of 17.6 & 16.9 respectively. This is shown in Fig. 5*B*. There are similar effects when the individual performs self-paced tapping of the thumb, middle, and little finger (Fig. 5 *C-E*). The size of the E2 component produced by index finger abduction is clearly reduced in all tasks. The percent EMG E2 modulations produced are 6.0, 0.0 & 12.2 respectively. The E1 and I1 modulations are unchanged producing percent EMG modulations of 16.9, 21.3 & 15.4 respectively for the E1 component and 19.7, 16.9 & 14.6 respectively for the I1 component. The size of the sensory volley recorded from the median nerve during the finger movements ranged from 3.0 - 3.4μV peak to peak. The background EMG level during each of the finger tapping movements ranged from 79 - 88μV.

Taking all the data together, the mean size of the E2 component decreased when finger tapping was performed whilst simultaneously abducting the index finger in 91% of all recordings (Fig. 6). Repeated measures analysis of variance (rmANOVA) revealed a

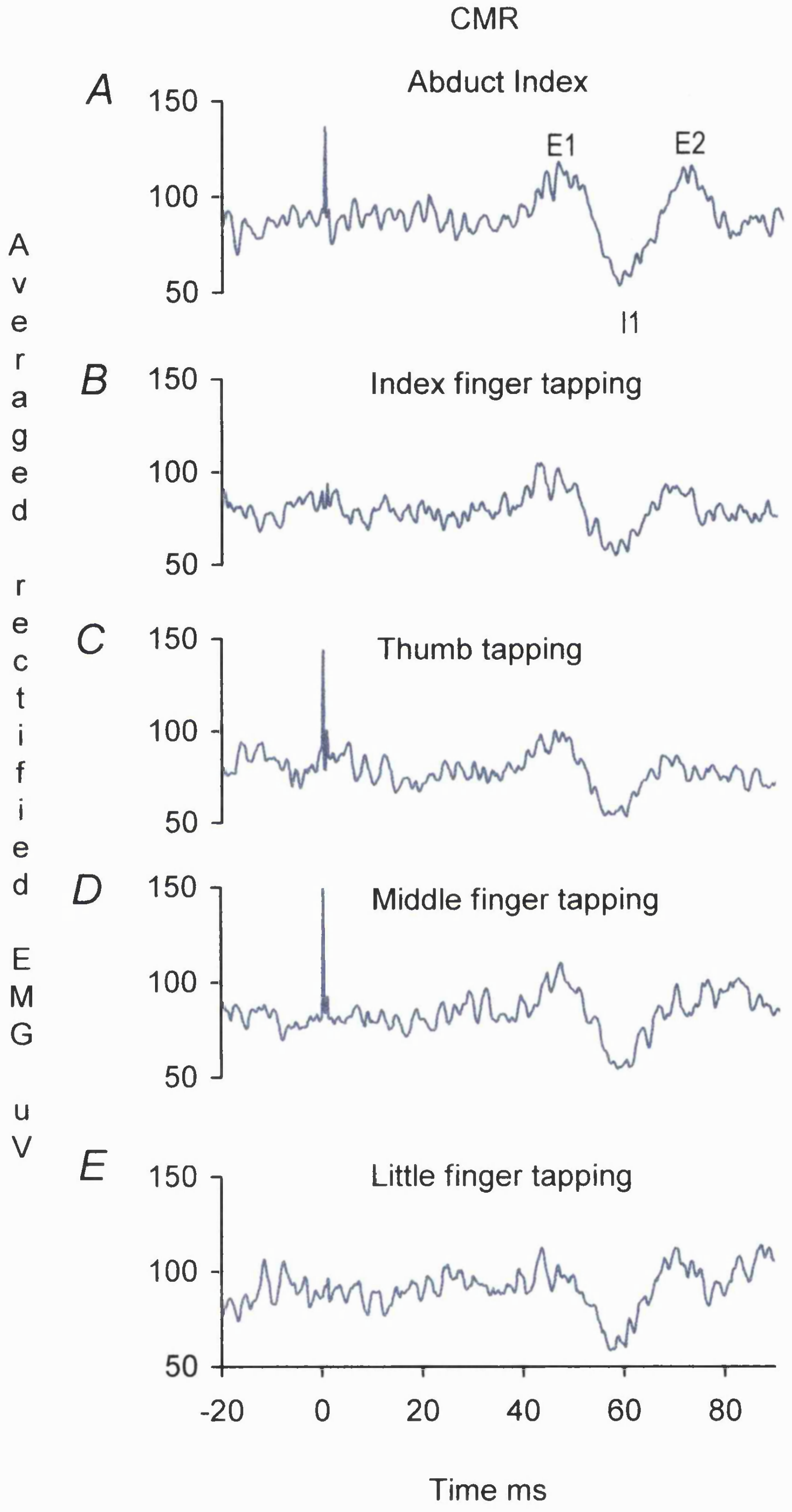

CMR
A
Abduct Index
E1
E2
I1
B
Index finger tapping
C
Thumb tapping
D
Middle finger tapping
E
Little finger tapping
150
100
50
-20
0
20
40
60
80
Time ms
Averaged rectified EMG uV

**Figure 5. Effect of finger movement on the components of the CMR recorded from 1DI following electrical stimulation of the digital nerves of the index finger**

*A,* Cutaneous reflex response recorded from 1DI following stimulation of the digital nerves of the index finger during a sustained voluntary abduction of the index finger, maintained at 10-20% of the MVC (Abd). A clear cutaneous reflex was observed consisting of an initial rise E1, followed by a decrease I1, followed by a second increase E2. *B-E,* Reflex recorded from 1DI following stimulation of the digital nerves of the Index finger during a sustained voluntary abduction of the index finger maintained at 10-20% of the MVC as in A with concomitant tapping of B, the index finger (Abd + I), C, the thumb (Abd +T) D, the middle finger (Abd+M), and E, the little finger (Abd +L). In each case the reflex component E2 is clearly reduced or abolished in the case of middle finger tapping whilst E1 and I1 remain unaltered. *A-E,* show the rectified and averaged EMG time locked to each stimulus, delivered at 5s$^{-1}$. 250 sweeps. All recorded in the same session.

significant decrease in the size of the E2 component recorded from 1DI during a sustained abduction of the index finger whilst simultaneously performing finger tapping compared to the size of the E2 component when simply abducting the index finger ($P < 0.05$ for each finger tapping movement task). Of the 15 subjects, 73% reported a decreased appreciation of the stimulus during tapping compared with abduction alone. Although the mean size of the I1 component was reduced particularly during little and middle finger tapping this change was not found to be statistically significantly different to index finger abduction ($P > 0.05$). The E1 component was unaltered during finger tapping ($P > 0.05$).

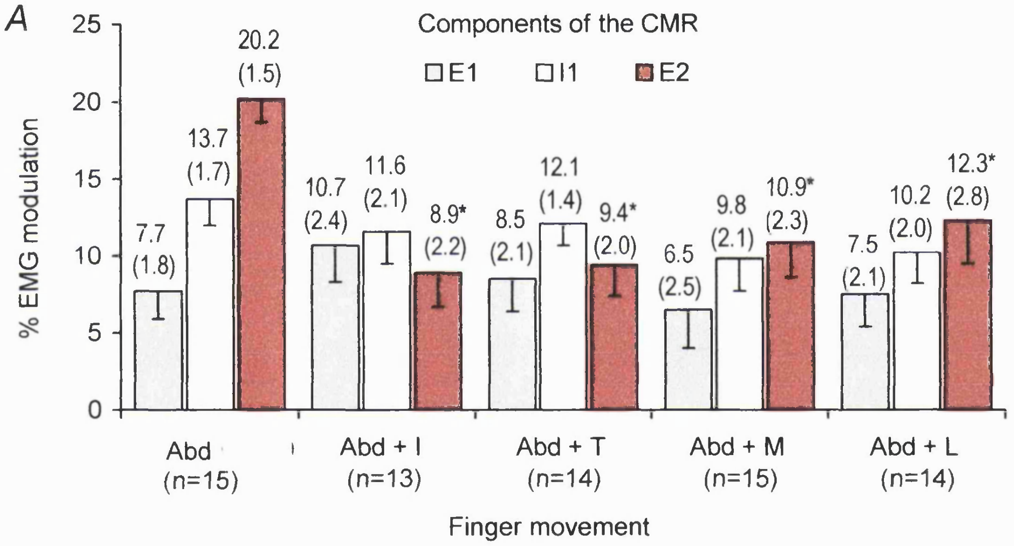


**Figure 6. Mean data (- 1 S.E.M) obtained from all subjects showing the effect of finger tapping upon the components of the CMR.**

Mean size of each component (top) and S.E.M (bracketed) are given above each bar for each chart. *A*, CMR recorded from 1DI following stimulation the of the index finger digital nerves during a sustained abduction of the index finger alone (Abd) contrasting the CMR obtained during index finger (Abd+I), thumb (Abd+T), middle finger (Abd+M), and little finger (Abd+L) tapping. Grey filled bars: mean size of E1 component. White filled bars: mean size of the I1 component. Red filled bars: mean size of the component E2. Significant differences were found in the size of the E2 component on comparing the differences between the means obtained during abduction and each finger movement (rmANOVA, $P < 0.05$, denoted *). Components E1 and I1 were not significantly altered (rmANOVA, $P > 0.05$ in both cases).

On first inspection of the chart illustrated in Fig. 6 it appears that there is a graded effect in the decrease in the size of the mean percent E2 EMG modulation. The maximal decrease in the size of the E2 component appears to occur when performing index finger or thumb tapping, whilst little finger tapping appears to have the least effect. However rmANOVA did not reveal a significant difference between which finger was performing the tapping and the resultant decrease in the size of the mean percent E2 EMG modulation ($P > 0.05$).

Fig. 7 shows the simultaneously recorded SEP obtained from S1 following stimulation of the digital nerves of the index finger in one subject. When the subject performs a simple abduction of the index finger (Fig.7*A*), approximately 20ms following stimulation there is an initial negative rising component, N20, followed by a positive down going component, P25. The peak-to-peak amplitude of the N20/P25 components measured 2.7µV. However when the subject performs tapping of a finger whilst simultaneously abducting the index finger there is a clear reduction in the size of the N20/P25 components (Fig. 7 *B-E*). The measured peak-to-peak amplitudes being 1.3µV during index tapping, 1.9µV during thumb tapping, 1.8µV during middle and 1.3µV during little finger tapping.

Combining all data together, the mean size of the amplitude of the N20/P25 and N20 SEP components are significantly reduced by finger tapping when compared to simple abduction of the index finger (rmANOVA, $P < 0.05$ in all finger movements). This is illustrated in Fig.8*B*. The size of the P25 SEP component was unaltered during finger tapping ($P > 0.05$). As with the CMR, pairwise comparisons failed to show that the decrease in the size of the N20/P25 components was dependent upon which finger was tapping ($P > 0.05$).

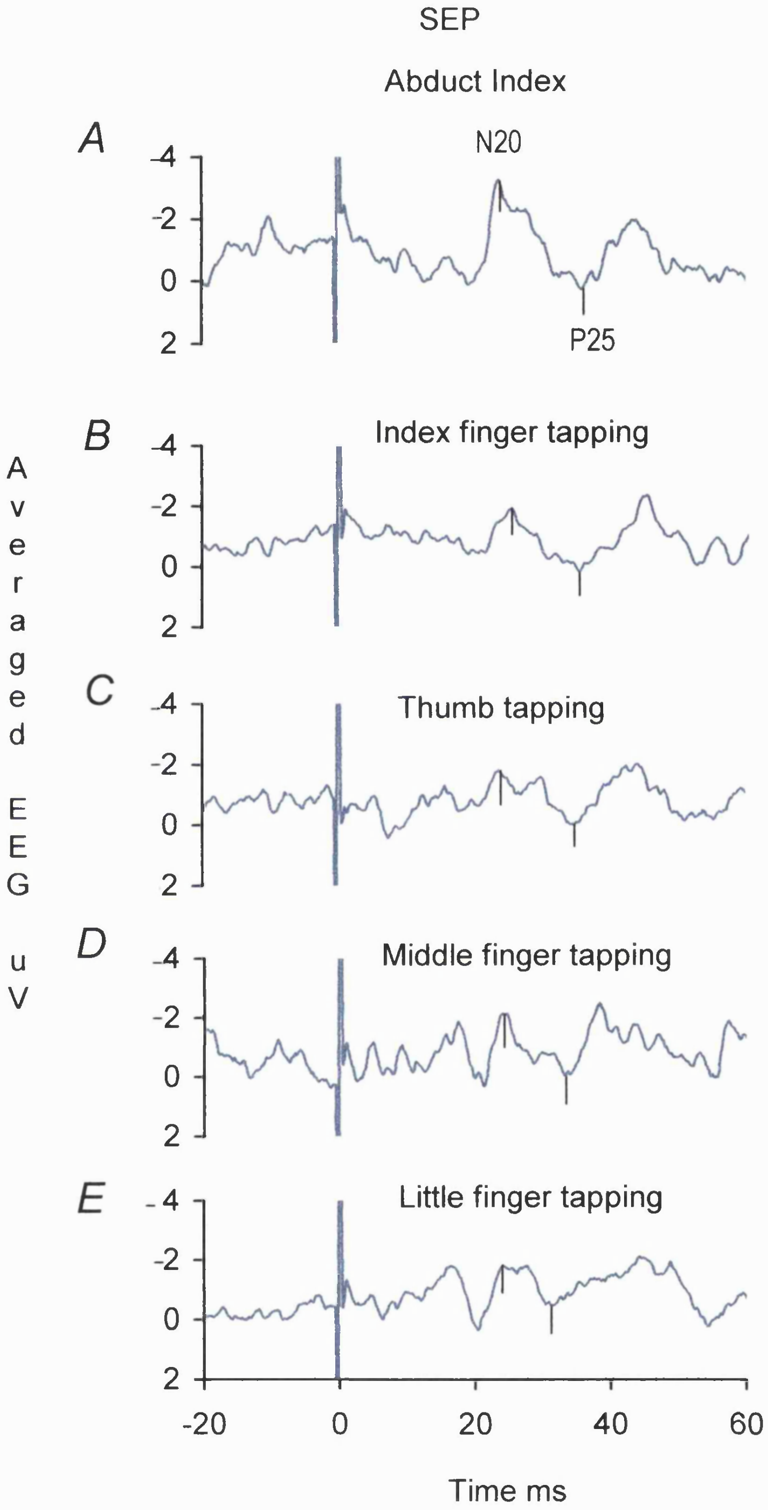

SEP
Abduct Index
A
N20
P25
-4
-2
0
2
B
Index finger tapping
C
Thumb tapping
D
Middle finger tapping
E
Little finger tapping
Averaged EEG uV
-20
0
20
40
60
Time ms

**Figure 7. Effect of finger movement on the N20/P25 components of the SEP recorded from the contralateral sensory cortex following electrical stimulation of the digital nerves of the index finger**

*A,* N20/P25 response recorded from the contralateral sensory cortex following stimulation of the digital nerves of the index finger during a sustained voluntary abduction of the index finger, maintained at 10-20% of the MVC (Abd). An initial negative rise N20, followed by a positive decrease, P25 is seen. Labelled on the trace. *B-E,* N20/P25 response recorded from the contralateral sensory cortex following stimulation of the digital nerves of the Index finger during a sustained voluntary abduction of the index finger maintained at 10-20% of the MVC as in A with concomitant tapping of B, the index finger (Abd + I), C, the thumb (Abd +T) D, the middle finger (Abd+M), and E, the little finger (Abd +L). In each case the response is clearly reduced. *A-E,* show the averaged EEG time locked to each stimulus, delivered at $5s^{-1}$. 500 sweeps (a 250 sweep average was obtained on 2 occasions in the same recording session and combined to give a 500 sweep average).

The size of the afferent volley recorded from the median nerve at the wrist and the background EMG levels are shown in Fig.8*C* for all subjects. It was found that finger tapping did not significantly alter the afferent volley to the spinal cord ($P > 0.05$) or background EMG ($P > 0.05$).

The Chi-square test for association performed upon the combined data showed a significant qualitative relationship between the decrease in the size of the E2 component of the CMR and the decrease in the size N20/P25 components of the SEP ($P < 0.05$). Given the small study sample the significance was verified by employing the Fisher's exact method ($P < 0.05$).

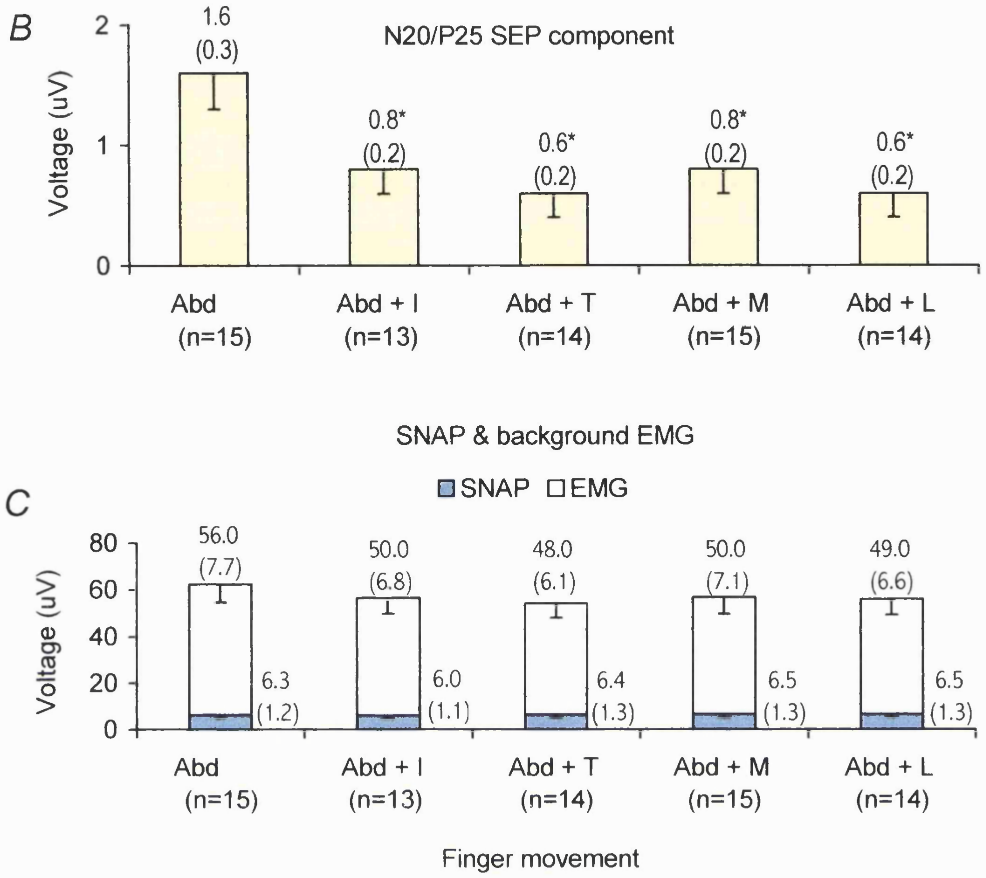


**Figure 8. Mean data (- 1 S.E.M) obtained from all subjects showing the effect of finger tapping upon the components of the SEP, SNAP and background EMG**

Mean size of each component (top) and S.E.M (bracketed) are given above each bar for each chart. *B*, N20/P25 SEP component recorded from the contralateral sensory cortex following electrical stimulation the of the index finger digital nerves during a sustained abduction of the index finger alone (Abd) contrasting the CMR obtained during index finger (Abd+I), thumb (Abd+T), middle finger (Abd+M) and little finger (Abd+L) tapping. Significant differences in the size of the N20/P25 SEP components were found on comparing the means obtained during abduction and each finger movement (rmANOVA, $P < 0.05$, denoted *). *C*, SNAP recorded from the median nerve at the wrist and background EMG recorded from IDI during index finger abduction following electrical stimulation of the index finger digital nerves for each finger tapping task performed as described in *B*. Blue filled bars: mean size of the SNAP recorded from the median nerve. White filled bars: mean size of the background EMG.

Fig. 9 shows the effect of concurrently tapping the ipsilateral foot whilst simultaneously abducting the index finger upon the CMR and SEP for a single subject.

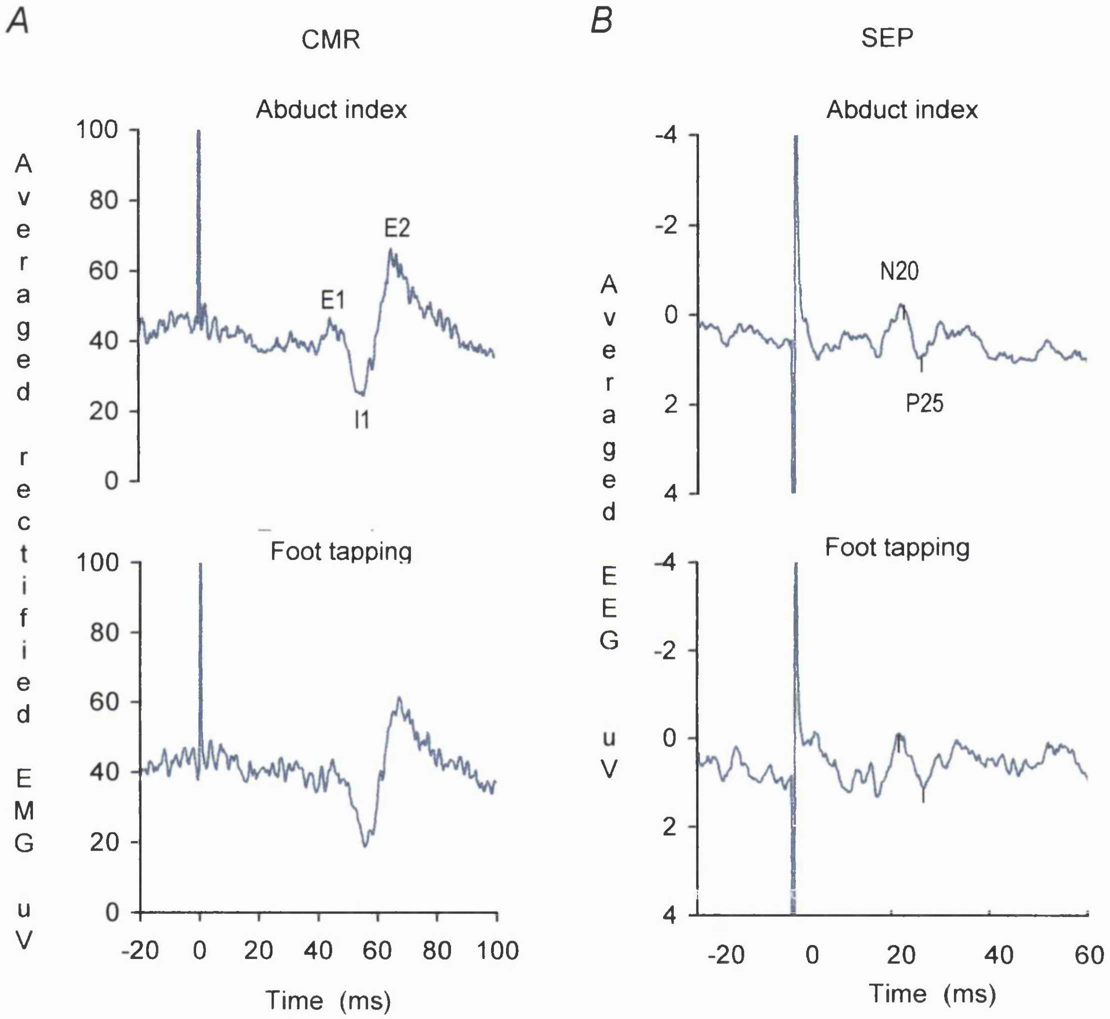


**Figure 9. Effect of ipsilateral foot movement on the components of the CMR recorded from 1DI and cortical SEP following electrical stimulation of the digital nerves of the index finger**

*A*, Cutaneous reflex response recorded from 1DI following stimulation of the digital nerves of the index finger during a sustained voluntary abduction of the index finger, maintained at 10-20% of the MVC (upper trace). A clear cutaneous reflex was observed consisting of an initial rise E1, followed by a decrease I1, followed by a second increase E2. This is similarly the case when performing concomitant ipsilateral foot tapping (lower trace). *B*, SEP recorded from the contralateral sensory cortex following stimulation of the digital nerves of the Index finger during a sustained voluntary abduction of the index finger maintained at 10-20% of the MVC (upper trace) producing a clear N20/P25 component compared with the N20/P25 SEP component obtained during concurrent ipsilateral foot tapping (lower trace). As with the CMR the SEP is unaltered. *A*, shows the rectified and averaged EMG time locked to each stimulus, delivered at $5s^{-1}$. 250 sweeps. *B*, shows the averaged EEG timelocked to each stimulus, delivered at $5s^{-1}$. 500 sweeps.

When the subject abducts the index alone following stimulation of the index finger digital nerves, a reflex response consisting an initial rise in EMG, E1, followed by a decrease, I1, followed by a second increase, E2 is elicited producing % EMG modulations of 11, 22 & 42 respectively. It is clearly evident that ipsilateral foot tapping does not have any effect upon the components of the reflex response, producing % EMG modulations of 11, 24 & 44 respectively.

There is no change in the size of the N20/P25 SEP components simultaneously recorded from the contralateral sensory cortex. The measured peak-to-peak amplitude was 2.1µV during abduction alone and 2.1µV during ipsilateral foot tapping. The ongoing EMG ranged from 34 - 35µV and the size of the SNAP recorded from the median nerve overlying the wrist was measured 4.4µV on each occasion.

Taking the data as a whole, the mean size of the E1, I1 & E2 components of the CMR and the N20/P25 components of the SEP were unaltered when concurrently tapping the ipsilateral foot in 100% of all recordings (n=4). The size of the components of the CMR recorded from 1DI and the sensory cortex during index finger abduction whilst concurrently tapping the foot showed no significant change when compared to the size of the components of the CMR and SEP recorded when simply abducting the index finger (rmANOVA, $P > 0.05$ in all cases). This was similarly the case for the SNAP and Background EMG levels ($P > 0.05$ in both cases). Illustrated in Fig.10.

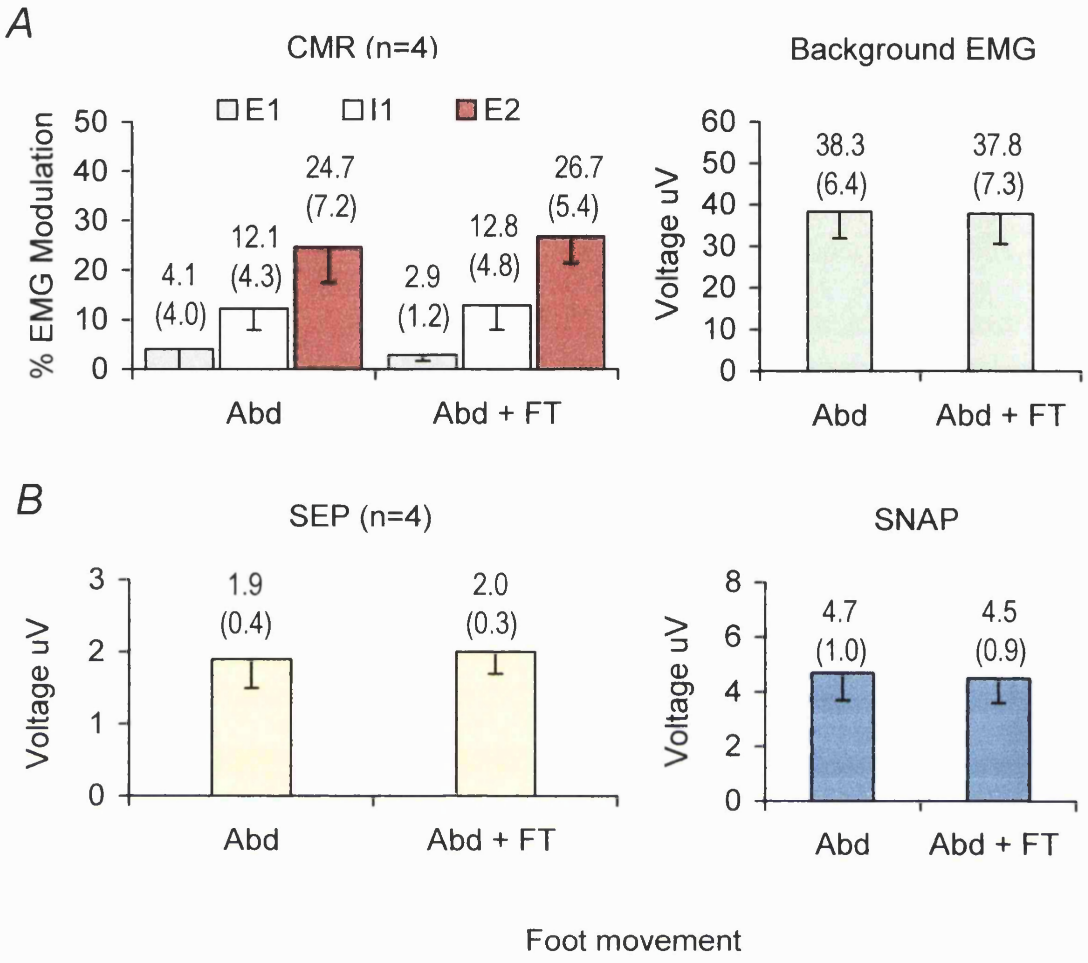


**Figure 10. Mean data (- 1 S.E.M) obtained from four subjects showing the effect of ipsilateral foot tapping on the components of the CMR, background EMG, SEP & SNAP**

Mean data value (top) and S.E.M (bracketed) are shown on the chart above each bar. *A*, CMR and background EMG recorded from 1DI whilst stimulating the digital nerves of the index finger during sustained abduction of the index finger alone (Abd) contrasting the CMR obtained during foot tapping (Abd + FT). Grey filled bars: mean size of the component E1 of the reflex. White bars: mean size of the I1 component of the reflex. Red filled bars: mean size of the component E2 of the reflex. Green filled bars: mean size of the background EMG. *B*, SEP recorded from the contralateral sensory cortex and SNAP recorded from the median nerve at the wrist. Yellow filled bars: mean size of the N20/P25 component of the SEP. Blue filled bars: mean size of the SNAP.

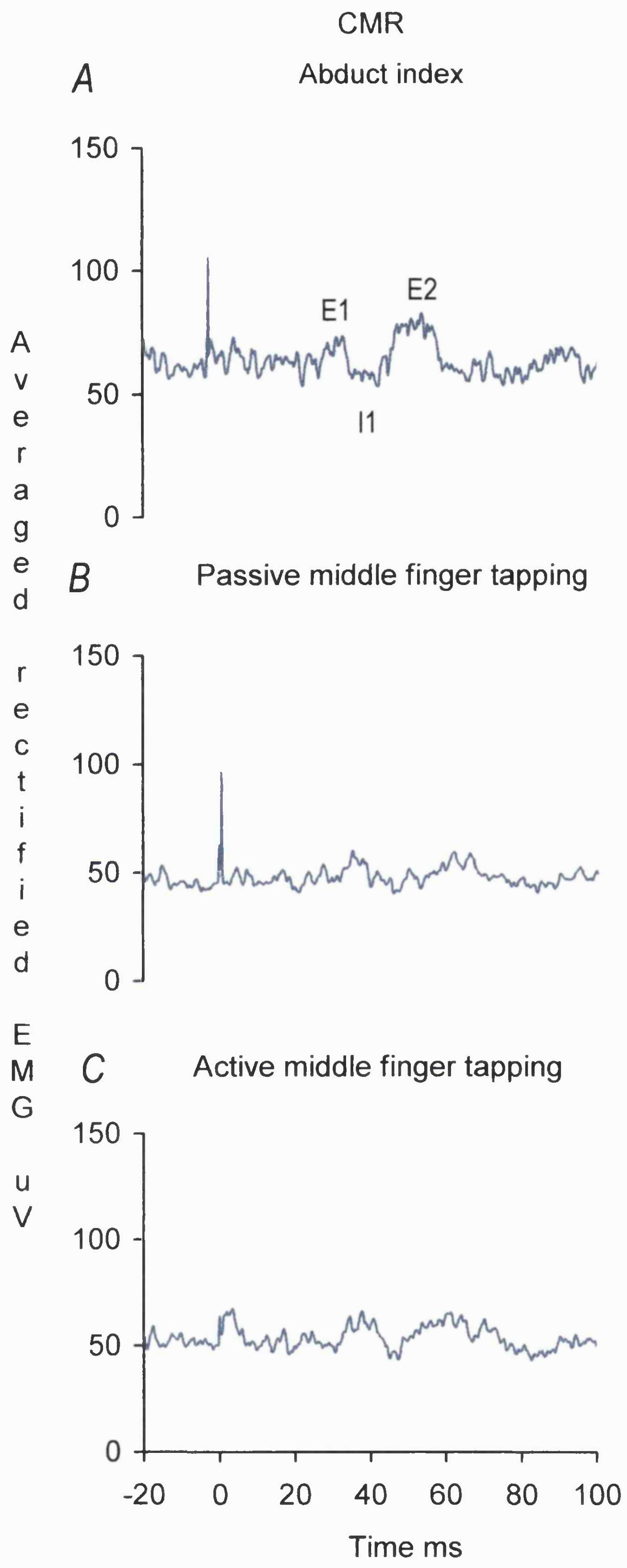
### *Experiment 3: Effect of active & passive middle finger movement*

The effect of active and passive middle finger movement on the averaged rectified EMG recorded from the 1DI muscle during a sustained voluntary abduction of the index finger in a single individual is shown in Fig. 11. During simple index finger abduction (Fig. 11*A*), stimulation of the digital nerves of the index finger elicits a triphasic response, consisting of the short latency increase in EMG, E1 followed by a decrease in EMG, I1 followed by a second increase in EMG, E2. The % EMG modulations produced were 8.9, 5.8 & 16.7 respectively. In contrast when passive middle finger tapping is performed whilst simultaneously abducting the index finger, there is a clear reduction in the size of the E2 component (Fig. 11*B*) of the reflex from 16.7 to 9.8. The E1 and I1 components did not appear to be greatly affected by passive finger middle finger movement producing % EMG modulations of 10.2 & 2.2 respectively. A similar component reduction is seen in the size of the E2 component when active middle finger tapping is performed from 16.7 to 10.2. The E1 and I1 components were unaffected by active finger tapping producing % EMG modulations of 10.2 & 3.2 respectively. The sensory nerve volley recorded from the median nerve at the wrist was 13.4 - 16.1µV respectively. The background EMG ranged from 49 - 62µV.

Figure 12*A* shows the simultaneously recorded SEP from the contralateral sensory cortex during simple abduction of the index finger evoked an up going negative potential, N20 followed by a positive down going potential, P25. The measured peak-to-peak amplitude of the N20/P25 SEP component produced was 3.0µV. When passive and active finger middle finger tapping is performed the size of the N20/P25 SEP component is reduced in both cases from 3.0 to 1.3 (Fig.12*B)* and 1.6µV (Fig.12*C*) respectively.

**Figure 11. Effect of passive & active middle finger movement on the components of the CMR recorded from 1DI following electrical stimulation of the digital nerves of the index finger**

*A* , Cutaneomuscular reflex response recorded from 1DI following stimulation during a voluntary contraction maintained at 10-20% of MVC. Stimulation elicits a response consisting of an initial EMG increase, E1, followed by a decrease, I1, followed by a second increase, E2. *B-C* , reflex recorded from 1DI following stimulation of the index finger digital nerves during a sustained voluntary index finger abduction maintained at 10-20% MVC as in *A* with concomitant passive middle finger tapping performed by the experimenter, *B* , and with concomitant active middle finger tapping performed by the subject, *C*. In both cases the size of the reflex response, E2 is clearly reduced during finger tapping whilst E1 and I1 reflex components are unaltered. *A-C,* show the rectified and averaged EMG time-locked to each stimulus, deliivered at 5 per second. 256 sweeps. All recorded in the same session



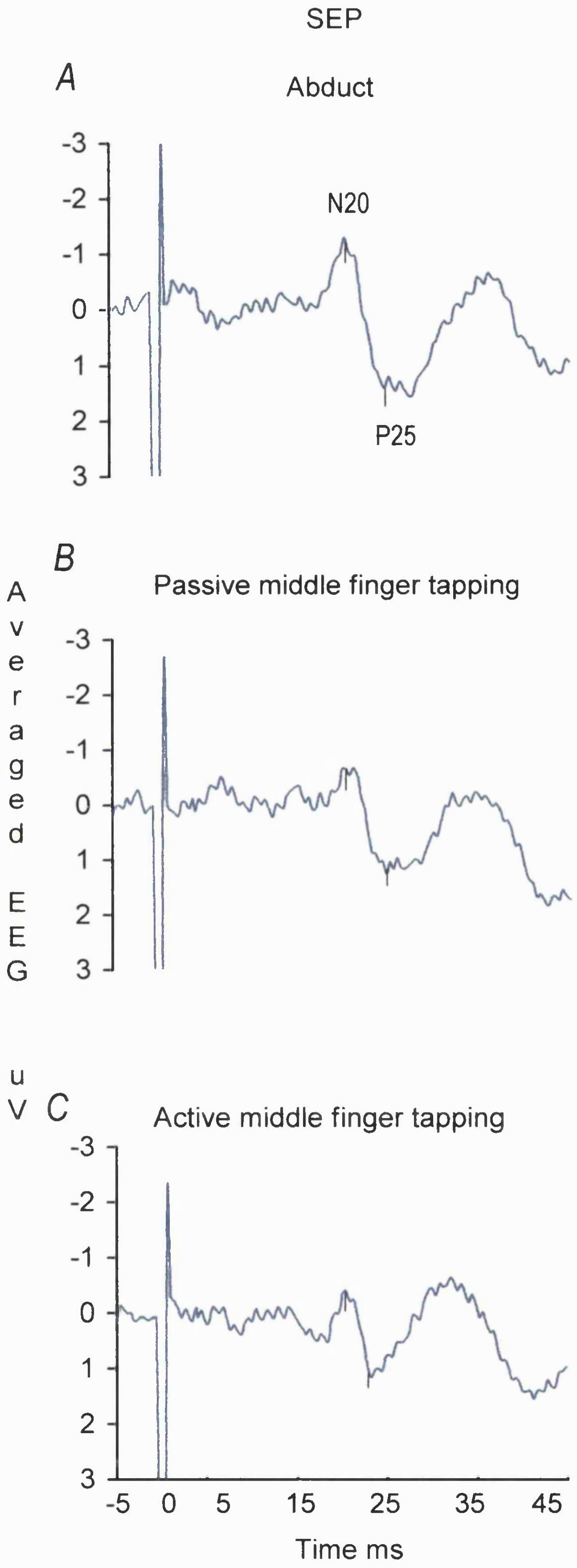


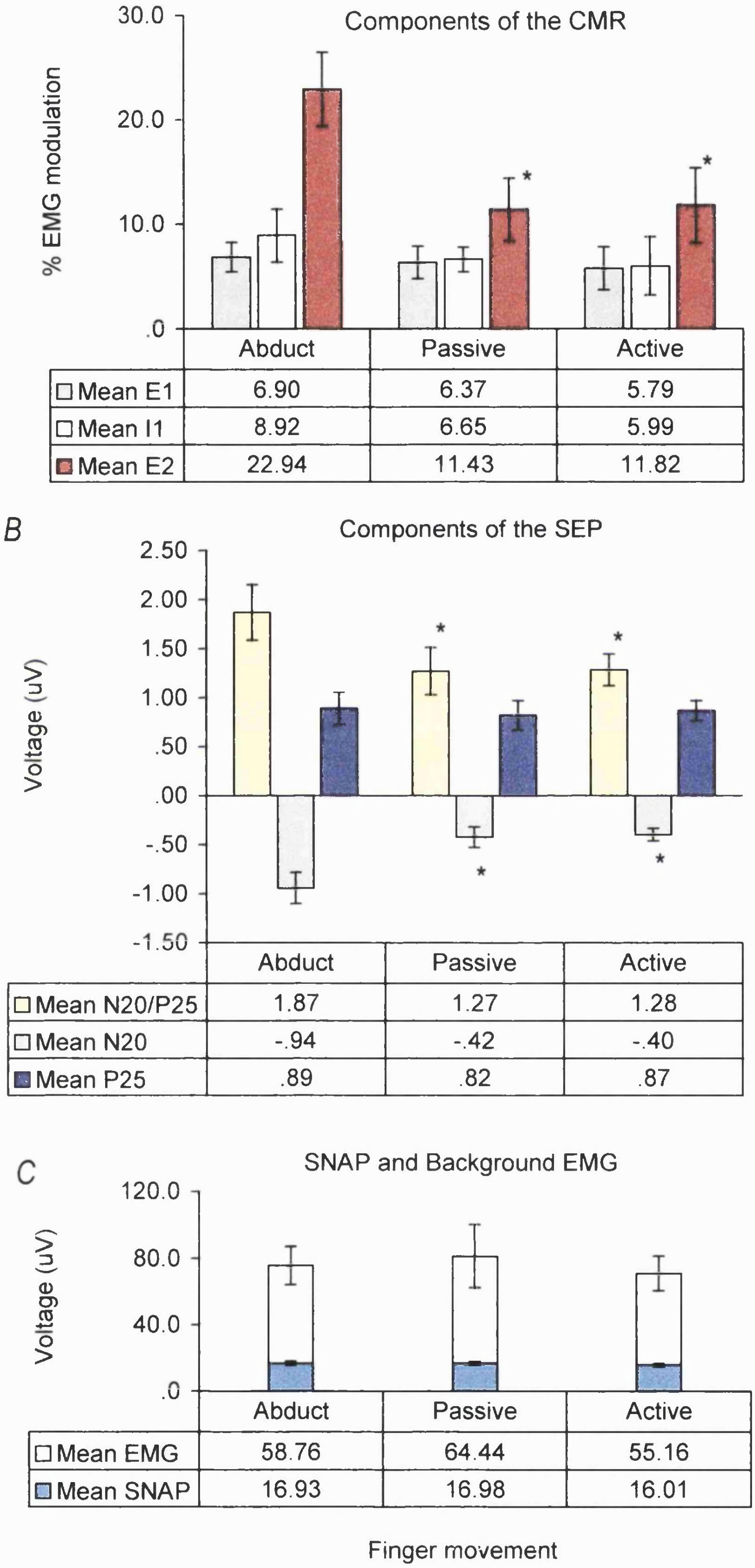
**Figure 12. Effect of passive & active middle finger movement on the N20/P25 SEP components recorded from the contralateral sensory cortex following electrical stimulation of the digital nerves of the index finger**

*A,* N20/P25 response obtained from the contralateral sensory cortex following index finger digital nerve stimulation during a sustained voluntary abduction of the index finger maintained at 10-20% MVC. Stimulation evoked a negative rise, N20, followed by a positive decrease, P25. *B-C* , N20/P25 response obtained from the contralateral sensory cortex following index finger digital nerve stimulation during a sustained voluntary abduction of the index finger maintained at 10-20% MVC as in *A* with concomitant passive middle finger tapping performed by the experimenter, *B,* and with concomitant active middle finger tapping by the subject, *C.* In both cases the size of the response is clearly reduced. *A-C* shows the averaged EEG time-locked to the stimulus, delivered at 5 sweeps per second. 256 sweeps.

Combining the data from all subjects together, there is a significant reduction in the mean size of the E2 component when passive and active middle finger movement is performed whilst simultaneously abducting the index finger compared to the mean size of the E2 component when abducting the index finger alone (rmANOVA, $P < 0.05$ in each case). The mean size of the E1 and I1 components of the reflex were not significantly altered during passive or active middle finger movement when compared to simple index finger abduction (rmANOVA, $P > 0.05$). This is illustrated in Fig.13.

Passive middle finger tapping produced a 51% decrease in the size of the E2 CMR component. A similar 58% decrease was produced during active middle finger tapping. Pairwise comparisons performed in the rmANOVA revealed no significant different between active and passive middle finger movement ($P > 0.05$).

Examining the data from all subjects (Fig.13) shows a 33% decrease in the size of the N20/P25 SEP components and a 55% decrease in the size of the peak amplitude of the N20 SEP component during passive middle finger tapping. In the same manner, active middle finger tapping produced a 32% decrease in the size of the N20/P25 SEP components and a 58% decrease in the size of the peak amplitude of the N20 SEP component. Significant differences were found in the N20/P25 and N20 SEP component when active and passive middle finger tapping were compared to simple index finger abduction ($P < 0.05$ in each case). The P25 SEP component was unaltered during passive and active middle finger tapping ($P > 0.05$). As with the E2 component of the CMR pairwise comparisons did not reveal any significant differences between active and passive middle finger movement ($P > 0.05$).



| | Abduct | Passive | Active |
|---|---|---|---|
| ☐ Mean E1 | 6.90 | 6.37 | 5.79 |
| ☐ Mean I1 | 8.92 | 6.65 | 5.99 |
| ■ Mean E2 | 22.94 | 11.43 | 11.82 |

| | Abduct | Passive | Active |
|---|---|---|---|
| ☐ Mean N20/P25 | 1.87 | 1.27 | 1.28 |
| ☐ Mean N20 | -.94 | -.42 | -.40 |
| ■ Mean P25 | .89 | .82 | .87 |

| | Abduct | Passive | Active |
|---|---|---|---|
| ☐ Mean EMG | 58.76 | 64.44 | 55.16 |
| ■ Mean SNAP | 16.93 | 16.98 | 16.01 |

**Figure 13. Mean data (+/- 1 S.E.M) obtained from all subjects showing the effect of passive & active middle finger tapping upon the CMR, SEP, SNAP & EMG**

Mean size of each component is given in a table below the chart. S.E.M is shown on each bart of the chart. *A,* CMR recorded from 1DI, following stimulation of the digital nerves of the index finger during a sustained abduction of the index finger(Abduct) compared to the CMR obtained during passive middle finger tapping by the experimenter(Passive) & the CMR obtained during active middle finger tapping by the subject (Active). Grey filled bars: mean size of the E1 component. White filled bars: mean size of the I1 component. Red filled bars: mean size of the E2 component. Significant differences were found on comparing the mean E2 component obtained during abduction and both middle finger movement (rmANOVA, $P < 0.05$,denoted * on the chart). E1 & I1 CMR components were not significantly altered (rmANOVA, $P > 0.05$).

*B,* SEP recorded from the contralateral sensory cortex following stimulation of the digital nerves of the index finger during a sustained voluntary abduction of the index finger contrasting the SEP obtained during passive & active middle finger tapping. Yellow filled bars: mean size of the N20/P25 SEP component. Grey filled bars: mean size of the N20 SEP component. Blue filled bars: mean size of the P25 SEP component. Significant differences were found in the size of the N20/P25 & N20 SEP components obtained during abduction and both middle finger movement (rmANOVA, $P < 0.05$ denoted * on chart). The size of the P25 SEP component was unaltered (rmANOVA, $P > 0.05$).

*C,* SNAP recored from the median nerve at the wriist & background EMG recorded from 1DI during abduction compared to passive & active middle finger movement. Filled blue bars: SNAP. White bars: background EMG. No significant difference was found on comparing the means obtained during abduction and both middle finger movement (rmANOVA, $P > 0.05$).

The Chi-square test for association performed on the combined data showed that there was a qualitative relationship between the decrease in the size of the E2 CMR component and both the N20/P25 and N20 SEP components during active ($P < 0.05$) and passive middle finger tapping ($P < 0.05$).

## Discussion

Experiments 1 & 2 in the present study have demonstrated that the E2 component of the CMR recorded from the 1DI muscle is reduced when active finger tapping is performed. The reduction in the size of the E2 component was found to be unrelated to which finger is tapping. This effect on the E2 component of the CMR is not seen when ipsilateral foot tapping is performed in place of finger tapping. The E1 and I1 components were found to be unchanged during either finger or foot tapping. It has also been shown that the reduction in the size of the E2 component seen during finger tapping is associated with a reduction in the size of the N20/P25 components of the SEP, reflecting the activities within areas 3b and 1 generated within the S1 in response to the afferent input (Desmedt & Tomberg, 1989).

The final experiment in the present study has demonstrated that the E2 component of the CMR recorded from 1DI and the N20/P25 & N20 SEP components are reduced during both passive and active middle finger tapping movements. The E1 and I1 CMR components and P25 SEP component are unaltered by passive and active middle finger tapping. There was found to be no difference between passive and active middle finger movement.

### *Sensory volley to the CNS*

The size of the SNAP recorded from the median nerve at the wrist was not significantly altered during the active or passive finger tapping. This indicates that the act of moving the finger has no effect on the afferent volley evoked by electrical stimulation of the index finger digital nerves. Therefore the reported decrease in the size of the E2 CMR and N20/P25 SEP components cannot be due to a change in the afferent input to the spinal cord.

### *E1 reflex component of the CMR*

The E1 component was unaltered during active and passive finger tapping, suggesting that the decrease seen in the present study must have occurred at a level above the spinal cord, as evidence suggests that E1 (Jenner & Stephens, 1982) is spinal whilst I1 and E2 components of the reflex are transcortical in origin (Mayston *et al.* 1997).

### *Explanations for the reduction in the size of the E2 component of the CMR and N20/P25 components of the SEP observed during finger movement*

The present findings have shown that during active and passive finger tapping there is a significant decrease in the size of the E2 component of the CMR, associated with a significant decrease in the size of the N20/P25 SEP components at the S1. These findings are concordant with the notion that the decrease in the size of the E2 component of the CMR is due to 'gating' of the afferent input during finger tapping as suggested in the hypothesis. Indeed 73% of the subjects in the present study reported a decreased awareness of the stimulus during tapping compared with abduction alone. There are a number of reports showing 'gating' of afferent information at different sites as it is propagated along the somatosensory pathway during active and passive movement. In animals 'gating' has been shown within the DCN (Ghez & Pisa, 1972), thalamus within VPN (Tsumoto *et al.* 1975), and S1 (Chaplin & Woolward, 1981). However in man, 'gating' of the afferent information is believed to occur within S1 with little contribution from the sub-cortical regions of the brain (Rushton *et al.* 1981; Hsieh *et al.* 1995). This suggests that the reduction in the size of the N20/P25 SEP components most likely reflects 'gating' of the afferent information within S1.

However Palmeri *et al.* (1999) have recently demonstrated that the motor cortex (M1) is also able to exert effects on the afferent activity at the level of the DCN & VPN during limb movement in cats. Using semi-chronic implanted microelectrodes, microstimulation was used to identify areas within the M1 with the ability to produce movement of a single limb joint. A number of cutaneous fields on the limb were stimulated and the neurones responsive to the stimulus identified in the DCN and VPN. Following this, the identified areas of the M1 were stimulated whilst simultaneously recording the effect on the DCN & VPN. Firstly, it was found that the areas concerned with producing limb joint movement in the M1 were able to modulate the afferent information to the M1 at the level of the DCN & VPN. Secondly, there was a higher incidence of excitatory effects when the stimulated cutaneous field was located nearest to the joint controlled by the area identified in the M1. As the stimulus became more distant to the joint the percentage of excitatory responses decreased, becoming more frequently inhibitory. Therefore it is possible that the reduction in the size of the afferent volley arriving at S1 seen in the present study may reflect 'gating' of the afferent information within the DCN/VPN imposed by M1 during movement as opposed to S1.

The present study also found that the size of the CMR and SEP were decreased during index finger tapping. This finding suggests that the CNS differentiated between the afferent information generated during index finger tapping and the afferent information generated by concomitant stimulation of the index finger digital nerves. It also suggests that during index finger tapping the CNS selectively chose to 'attend' to the afferent information generated by the index finger tap rather than the afferent information generated by the concomitant electrical stimulus, reflected as the observed decrease in the size of the CMR and SEP. These suggestions are supported by a recent study that has found that during lower limb cycling movement there is selective attention to the afferent information during different stages of the step-cycle reflected by changes in the SEP evoked from the sural nerve. In this manner there appears to be a task relevant modulation of the afferent information (Altenmüller *et al.* 1995).

### *The I1 component of the CMR*

Given the transcortical origin of the I1 and E2 components of the CMR (Mayston *et al.* 1997), it is surprising that finger tapping did not alter the size of the I1 component of the reflex in the present study. Increasingly it has become apparent that the I1 has different characteristics to the E2 component of the CMR. Harrison *et al.* (2000) have demonstrated that the I1 component shows little habituation in comparison to the E2 component, which habituates much more readily. One possible explanation for these findings may relate to differences in the route of mediation of each component. It is possible to suggest that the I1 and E2 components might be mediated via a different transcortical pathway. There is evidence to suggest that there is a direct pathway from the thalamus to the motor cortex (Slimp *et al.* 1986; Sonoo *et al.* 1991). It is possible to speculate that the I1 component may be mediated via this route whilst the longer latency of the E2 component may result from a relay including thalamus, sensory cortex, and motor cortex.

### *Specificity of the effect*

To further quantify the specificity of this effect complimentary studies were performed in the second experiment in which four subjects performed ipsilateral foot tapping whilst abducting the index finger. In this case there was no reduction in the size of the E2 component of the CMR or N20/P25 SEP component during tapping. This finding provides evidence that the reduction in the size of the CMR and digital nerve SEP which occurs during finger tapping, is not unspecific to finger movement, although further experiments are required to see if less remote areas of the body such as the arm or ipsilateral hand could produce similar effects to the finger tapping performed in this study.

### *Active versus passive middle finger movement*

The present study has found no significant difference between the size of the reduction of the CMR and SEP component recorded during active and passive middle finger movement. The present findings concur with the study of Rushton *et al.* 1981, in which the digital nerve SEP following stimulation of both the thumb and index finger during active and passive flexion of the distal phalanx of thumb or digit was recorded. The study found that in 7 out of the 8 subjects both active and passive flexion of the distal phalanx was equally as effective at reducing the early and middle latency SEP cortical components (Rushton *et al.* 1981*)*. Other studies have reported similar findings in the mixed nerve SEP (Jones *et al.* 1989; Huttunen & Hömberg, 1991. The ability to recognise an object during passive and active touch also appears to be the same. A number of experiments that have shown that there is no difference between active and passive touch in the ability to recognise 2 –D shapes (Johansson & La Motte, 1983) or surface irregularities (Schwartz *et al.* 1975).

### *N20 and P25 SEP components recorded during active and passive middle finger movement*

The results in this study have shown that passive and active middle finger movement reduce the size of the N20/P25 and N20 SEP components but do not affect the P25 SEP component elicited following index finger digital nerve stimulation. Few studies have recorded the digital nerve SEP during different finger movements. Rushton *et al.* 1981 reported a reduction in the size of the N20 and N20/P25 (labelled P30 in their study) SEP component during passive and active finger movement following digital nerve stimulation of the thumb (Rushton *et al.* 1981). Although the N20 and N20/P25 SEP components were clearly reduced only the N20/P25 reduction was statistically significant. The P25 component was not measured. More recently Waberski *et al.* presented contrasting evidence suggesting that the N20 SEP component is only reduced a little whilst the P25 SEP component is markedly reduced during explorative finger movement (Waberski *et al.* 1999). The discrepancies between the findings reported in these studies including the present study may be explained by the fact that when the finger movement tasks performed by the subjects are compared in each of the studies, they are found to be very different from each other.

### *Mechanisms involved in producing the 'gating' effect*

The reduction in the size of the E2 CMR and N20/P25 and N20 SEP components observed during passive finger movement suggests that proprioceptive feedback from the finger movement and cutaneous afferent input generated by the tap is able to mediate 'gating' of afferent information. Cheyne *et al.* 1997 have shown using MEG that the early movement evoked field (MEF) generated during self-paced movements reflect sensory feedback from the periphery (Cheyne *et al.* 1997). The present finding however is based upon the assumption that corollary discharges to other motor regions are not generated during the passive middle finger movement. It is possible to suggest that anticipation of the passive middle finger movement alone may trigger collary discharges, which might influence the 'gating' of afferent input. It is likely that both mechanisms contribute to the 'gating' effect. The role of proprioceptive feedback and cutaneous afferent input in mediating the 'gating' effect could be further explored by carrying out experiments in which the fingertips are anaesthetised.

## Conclusions

In conclusion, the present study has demonstrated that during finger tapping there is a significant decrease in the size of the E2 component of the CMR that is associated with a decrease in the size of the N20/P25 SEP components. The most likely explanation for these findings is that the decrease in the size of the E2 component results from 'gating' of the afferent information within the sensory cortex during finger tapping. The significant decrease in the size of the E2 component of the CMR and N20/P25 and N20 components of the SEP seen during passive finger movement suggests that sensory feedback from the finger is involved in the mediation of the 'gating' of afferent information.

In the next section the effect of index finger movement tasks upon the components of the CMR recorded from the 1DI muscle following electrical stimulation of the digital nerves of the index finger and the index finger digital nerve SEP are investigated.

# Section 2: Effect of attended and unattended index finger movements upon the cutaneomuscular reflex recorded from the first dorsal interosseous muscle in man

## Summary

1. Recordings were obtained from 21 healthy adults. The CMR was recorded from the 1DI muscle, the SEP was recorded from the contralateral sensory cortex, and the SNAP was recorded from the median nerve whilst the digital nerves of the index finger were electrically stimulated.

2. Each subject performed the following finger movement tasks on 2 occasions and in a random order:

   *(a)* A sustained voluntary light abduction/flexion of the index finger (NAT HH).

   *(b)* Using only the index finger, subjects identified the shape of letters cut out into a foam mat (ID).

   *(c)* Subjects moved the index finger randomly over a foam mat without letter cut outs. On this occasion there was nothing to identify on the foam mat (NO ID).

   *(d)* Subjects performed task as per (c) whilst simultaneously performing mental arithmetic (MATHS).

   *(e)* Small self-paced tapping of the index finger (TAP).

   *(f)* The subject's hand was relaxed, without index finger movement (AT REST).

3. The size of the E2 and I1 reflex components were significantly reduced during index finger tapping (TAP) and the index finger letter identification (ID) task (rmANOVA, $P < 0.05$ in each case).

4. Random index finger movement (NO ID) and random index finger movement with concomitant mental arithmetic (MATHS) did not significantly reduce the size of the E2 and I1 reflex components (rmANOVA, $P > 0.05$ in each case).

5. The size of the E1 component of the reflex was not significantly altered during any of the index finger movement tasks (rmANOVA, $P > 0.05$ in all cases).

6. The size of the background EMG and SNAP recorded from the median nerve overlying the wrist were independent of the index finger tasks (rmANOVA, $P > 0.05$ in each case).

7. The size of the N20/P25 SEP component was significantly reduced during the random index finger (NO ID), random index finger with concomitant mental arithmetic (MATHS) and during index finger tapping task (rmANOVA, $P < 0.05$ in each case).

8. There were no significant changes in the size of the N20/P25 SEP component when the index finger was used to identify letters (ID) or during a sustained light abduction/flexion of the finger (rmANOVA, $P > 0.05$ in each case).

9. It was found that the size of the N20 SEP component was significantly reduced during all index finger movement tasks (rmANOVA, $P < 0.05$ in each case) except during a sustained light abduction/ flexion of the index finger (rmANOVA, $P > 0.05$).

10. The size of the P25 SEP component was unaltered during each of the finger movement tasks (rmANOVA, $P > 0.05$).

11. A comparison of the components of the reflex obtained during the random index finger movement (NO ID) and identification of letters using the index finger (ID) revealed a number of significant differences. The size of the E2 and I1 reflex components were significantly reduced during the identification task (ID) (rmANOVA, $P < 0.05$) but not

during the random index finger task (NO ID) (rmANOVA, $P > 0.05$). Neither movement task affected the size of the E1 component (rmANOVA, $P > 0.05$).

12. On comparing the size of the P25 SEP component obtained during random finger movement (NO ID) with index finger letter identification (ID), a significant increase in the size of the P25 SEP component was found during the index finger letter identification task when compared to the random index finger task (rmANOVA, $P < 0.05$).

13. The size of the N20/P25 and N20 SEP component obtained during both the random index finger movement (NO ID) and during letter identification (ID) using the index finger were not significantly different when compared to each other (rmANOVA, $P < 0.05$ in each case).

14. During the index finger letter identification (ID) task it was found that 47% of the group identified all letter shapes correctly (Group 1:*correct*) whilst 53% failed to correctly identify all letter shapes (group 2:*incorrect*).

15. The mean size of the reflex components E1, I1 and E2 obtained from the subjects of group 1:*correct* were found to be significantly greater when compared to the mean size of each of the reflex components of group 2:*incorrect* recorded during the index finger identification (ID) task (unpaired t-test, E1, $P = 0.021$; I1, $P = 0.041$; E2, $P = 0.047$).
16. The mean size of the N20/P25, N20 and P25 SEP components obtained from the subjects of group 1:*correct* were not significantly different when compared to the mean size of each of the SEP components obtained from the subjects of group

2:*incorrect* during the index finger identification (ID) task (unpaired t-test, N20, *P* = 0.102; P25, *P* = 0.201; N20/P25, *P* = 0.157).

17. The mean number of letters identified by subjects of group 1:*correct* was not significantly different when compared to the subjects of group 2:*incorrect* during the index finger identification (ID) task (unpaired t-test, *P* = 0.174).

18. It was found that there was no significant difference between the number of letter shapes correctly scored during the first and second acquisition for the subjects of group 1:*correct* or for the subjects of group 2:*incorrect* (unpaired t-test, group 1:*correct, P* = 0.701; group 2:*incorrect, P* = 0.456).

19. In conclusion the present study has shown a number of task-dependent changes in the I1 and E2 reflex components and the N20 and N20/P25 SEP components. It has also been demonstrated that activities in area 1 of S1 are enhanced during a task which requires the subject to pay attention compared to a similar task that does not require the subject to pay attention. One possible explanation for this finding is that it reflects changes in attention within S1.

# Introduction

It has been demonstrated in the previous section, that during finger tapping the size of the transcortical E2 reflex component recorded from the 1DI muscle following index finger digital nerve stimulation is significantly reduced. Furthermore the reduction in the size of the E2 component is associated with a 'mirrored' reduction in the size of the afferent volley arriving at the sensory cortex during finger tapping. Expanding upon these results, this section reports the findings of experiments in which the index finger has been used to perform a number of finger movement tasks whilst recording the reflex from the 1DI muscle, the SEP from the contralateral sensory cortex and the SNAP from the median nerve overlying the wrist following stimulation of the digital nerves of the index finger.

Previous studies have shown that the size of the N20/P25 (labelled P30 in study) components of the SEP evoked by digital nerve stimulation, reflecting the afferent volley arriving at S1 in area 3b and subsequently area 1 is reduced or 'gated' during movement (Rushton *et al.* 1981). Evidence suggests that movement per se is not essential for 'gating' (Jiang *et al.* 1990). However, the nature of motor activity evoked during movement appears to influence the 'gating' of the afferent information. For example, Dimitrov *et al.* 1989 showed that the size of the components of the SEP evoked following median nerve stimulation at the wrist were unaltered during a sustained isometric hold, whilst Rushton *et al.* 1981 showed that the speed of finger movement could influence the 'gating' effect seen upon the SEP evoked following digital nerve stimulation.

In addition, a number of studies in man have reported changes in the cortical components of the SEP to mixed and digital nerve stimulation during exploratory finger movements, but the findings are varied. Knecht *et al.* 1993 showed that during exploration of an object that the size of the size of the N20 SEP component was reduced, this component was followed by a second novel negative up-going component occurring at 28ms that was only evident during exploration (Knecht *et al.* 1993). Huttunen & Hömberg, 1991 showed that the size of the N20 and P25 SEP elicited following stimulation of the median nerve at the wrist was reduced during an exploratory task. Similarly, a more recent study by Hoshiyama & Kakigi, 1999 showed that during writing using the dominant hand that the size of the SEP N20 and P25 components elicited by median nerve stimulation were reduced.

Furthermore, there is also evidence that when a subject performs a task that requires the subject to pay attention, it is found that the level activation of S1 and S2 is greater when compared to a similar task not requiring the subject to pay attention (Johansen-Berg *et al.* 2000).

Given the aforementioned evidence the aim of the present experiments is to investigate the effect of performing different movement tasks using the index finger following index finger digital nerve stimulation upon the size of the reflex from 1DI whilst simultaneously recording the contralateral SEP from the sensory cortex. It is hypothesised that tasks using the index finger that require the subject to pay attention will selectively cause the CNS to attend to either the afferent information generated following digital nerve stimulation of the index finger or the afferent information generated by the task, reflected as a decrease or increase in the size of the components of the reflex response or digital nerve SEP.

## Methods

### *Subjects*

With local ethical committee approval, cutaneomuscular reflexes, digital nerve somatosensory evoked potentials, and sensory nerve action potentials were recorded from the preferred hand of 21 healthy subjects, aged 20-59 years (11 female). All subjects gave informed consent. The experimental protocols were performed in accordance to the guidelines set out in the Declaration of Helsinki, 1964.

### *Cutaneomuscular reflexes*

The ongoing surface EMG was recorded from the 1DI muscle in the same manner as described in section 1.

### *Digital nerve somatosensory evoked potentials*

Simultaneous recordings of the ongoing EEG were made from the sensory cortex contralateral to the side of stimulation during digital nerve stimulation in the same way as that described in section 1 with one exception, a reference electrode was attached to the scalp over the mid-frontal region which is located at a distance of 30% between the nasion and inion in the mid-line of the scalp, Fz.

### *Sensory nerve action potentials*

The same method as described in section 1 was used to record the sensory nerve action potential from the median nerve at the level of the wrist.

### *Digital nerve stimulation*

Stimulation of the digital nerves of the index finger was performed as per section 1.

### *Experiment*

Cutaneomuscular reflexes, digital nerve somatosensory evoked potentials, and sensory nerve action potentials were recorded, following digital nerve stimulation of the index finger. Each subject performed the following finger movement tasks:

*(a)* NAT HH: a sustained voluntary light abduction/flexion of the index finger.

*(b)* TAP: small self-paced tapping of the index finger.

*(c)* ID: a manufactured foam grid consisting of 6 letter cut outs was placed in front of the subject. With eyes shut and using only the index finger to search, subjects were asked to identify the letter, tell the experimenter and then move onto the next letter. A correct or incorrect identification was recorded for each letter. Subjects were shown a test grid with a letter cut out during the explanation of the task, but there was no prior knowledge of the letters to be used during the task. In addition it was explained to the subjects that they could spend as much time as required identifying each letter, as it did not matter how many letters were identified. The important point was made that subject should concentrate on correctly identifying the letter shape.

*(d)* NO ID: a manufactured foam grid as in (c) but without the presence of the letter cut outs was placed in front of the subjects. Subjects moved the index finger over the foam grid with eyes shut. On this occasion there was nothing to identify. Subjects were instructed randomly move over the grid and not to make patterns with the index finger.

*(e)* MATHS: task as per (d) whilst simultaneously performing mental calculations (either adding the number 7 together until reaching 507 or subtracting 7 until 0 is reached).

*(f)* AT REST: relaxed hand and muscle without index finger movement.

The experimenter monitored the ongoing EMG produced during each task (a)-(f). Each experiment was performed twice and in a random order. Subjects were rested for a few minutes between each task. Data were excluded if the subject was unable to perform the task.

### *Analysis*

#### *Cutaneomuscular reflexes*

The amplified and filtered EMG signal was rectified and then averaged time-locked to the stimulus for 250 sweeps. The size of each of the reflex component E1, I1 and E2 recorded from 1DI were measured in a manner identical to that described in section 1.

In addition, the SigAvg program software was used to save each individual sweep constituting the final 250 sweep average, individual sweeps with little or no EMG were excluded from the final average. This analysis was performed upon the amplified, filtered and rectified EMG signal obtained during the index finger identification task (ID) and random index finger movement (NO ID) in a number of subjects.

#### *Digital nerve somatosensory evoked potentials*

The EEG activity was averaged time-locked to the stimulus for 250 sweeps. The peak-to-peak amplitude of the N20-P25 component was measured from the two recordings by taking the percentage modulation measured for each of the 250 sweeps and calculating the mean percentage modulation. Measuring from each individual 250 average allowed more data to be included into the analysis.

#### *Sensory nerve action potentials*

The size of the SNAP was measured as per section 1.

### *Statistical analysis*

The normality of the data was established as per section 1. The significance of any effect of each finger movement task upon on the size of the CMR, SEP, and SNAP was examined by performing repeated measures analysis of variance (rmANOVA) and the unpaired t-test. The level of significance was set at $P < 0.05$.

#### *Type I errors & the Bonferroni adjustment*

The t-tests employed in this section assume that each observation within a group of observations is sampled independently of each other. Failure to observe this assumption may bias the sample group, resulting in an increased risk of erroneously rejecting the null hypothesis ($H_0$) when in fact the $H_0$ is true. In statistical terms incorrectly rejecting the $H_0$ when the $H_0$ is true is known as a type I error (Samuels & Witmer, 1999*a*). One way of reducing the occurrence of such an error is to employ multiple comparison tests such as an rmANOVA. Another way is to perform an adjustment using the Bonferroni method (Samuels & Witmer, 1999*b*).

The Bonferroni method is a technique, which allows multiple comparisons to be made by adjusting the level of statistical significance relative to the number of hypotheses to be tested. For example, three hypotheses are tested separately using a t-test at a 0.05 level of statistical significance. Each t-test gives rise to a $P$ value, which when compared to the selected 0.05 level of significance determines whether the $H_0$ is true or false. At this point to reduce the risk that a type I error may have occurred, the Bonferroni method can be employed. It is calculated in the following way:

$$\frac{\text{Selected level of statistical significance}}{\text{Number of hypotheses tested}} = \frac{0.05}{3} = 0.0166666\ldots \text{ reoccurring.}$$

In statistical terms this is known as a Bonferroni adjustment. Using this method to adjust the *P* value, gives a 5% level of protection against a type I error occurring at a statistical significance level of 0.05. Now the new level of statistical significance with the adjustment is 0.0166666... reoccurring. Therefore a statistically significant result will not be reported unless the *P* value generated by each t-test is less than 0.0166666... reoccurring. This adjustment can be used on many tests including Chi-square, t-test & Mann-Whitney. There are two main disadvantages when using this adjustment, firstly it is very conservative and secondly it can only be employed if the exact *P* values are given.

In relation to the present thesis, the exact *P* values calculated using t-tests have been given in section 2. This allows any reader of the present thesis to perform the Bonferroni adjustment if it is felt that the observations sampled in this section are not sufficiently independent of each other.

## Results

Fig.14 shows the effect of simultaneously performing each of the different finger movement tasks upon the averaged rectified EMG recorded from 1DI in one subject. During a light abduction/flexion of the index finger (NAT HH), stimulation of the digital nerves of the index finger elicits a triphasic reflex response (Fig14*B*), consisting of a short latency increase in EMG, E1, followed by a decrease, I1 & a second larger EMG increase, E2 producing % EMG modulations of 14.1,19 & 18.8 respectively. Similarly when the subject performs a random movement of the index finger without the need to identify whilst simultaneously performing mental calculations (MATHS) or randomly moving the index finger without the need to identify (NO ID), there is little change in the evoked response, producing E1, I1 & E2 % EMG modulations for each task of 17.8, 17.1 & 24.6 (Fig.14*C*) and 18.3,18,1 & 16.0 (Fig.14*D*) respectively. In contrast when the subject performs the index finger movement task that requires the subject to identify the letter cut outs (ID) or tap the index the index finger (TAP IF) the size of the I1 and E2 reflex components are reduced whilst the size of the E1 reflex component appears unaltered. The % EMG modulations produced for the E1, I1 and E2 components for the identification task were 11.6, 10.1 & 5.2 (Fig.14*E*) and 16.1, 15.1 & 8.1 (Fig.14*F*) for the index finger tapping task. When the hand and muscle was relaxed and resting still (AT REST), no response was elicited (Fig.14*A*). The size of the SNAP recorded from the median nerve overlying the wrist ranged from 15.7 to 16.4µV and the background EMG ranged from 14-23 µV.

When the data from all 21 subjects are combined (Fig.15), the mean size of the E2 and I1 components of the reflex response recorded from 1DI following index finger digital nerve stimulation are significantly reduced when the index finger is tapping (TAP IF) or used to

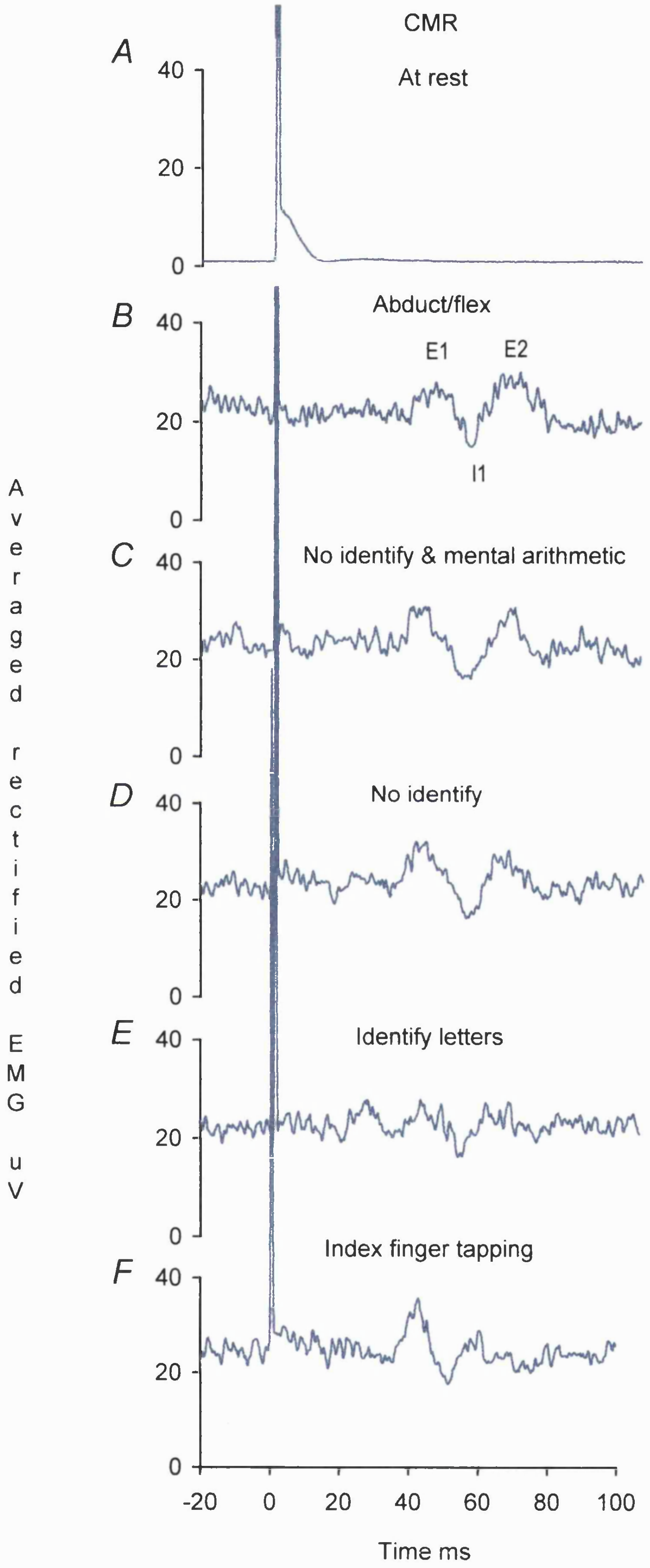
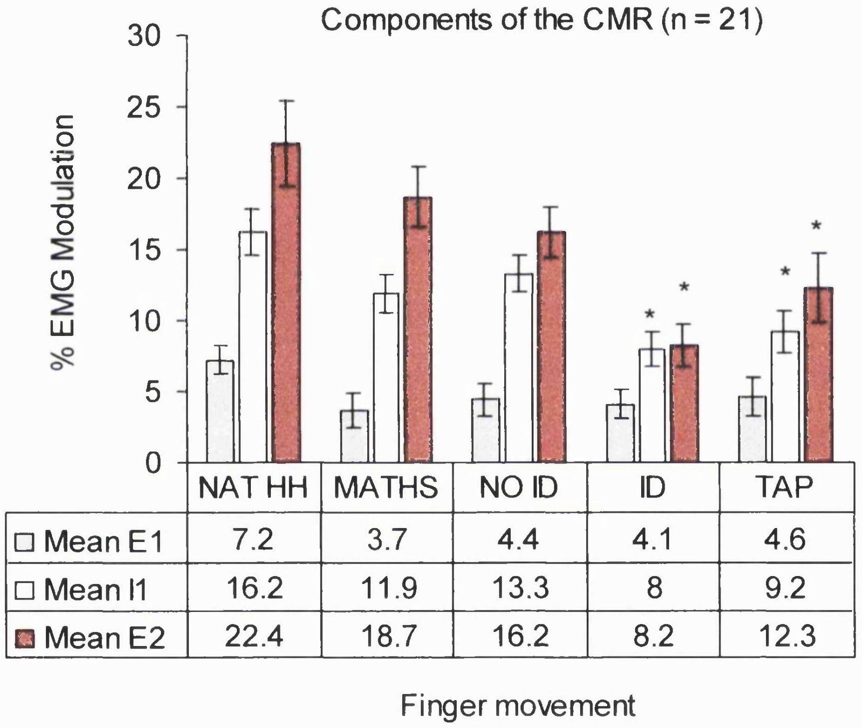

A
CMR
At rest
40
20
0
B
Abduct/flex
E1
E2
I1
40
20
0
C
No identify & mental arithmetic
40
20
0
D
No identify
40
20
0
E
Identify letters
40
20
0
F
Index finger tapping
40
20
0
-20
0
20
40
60
80
100
Time ms
Averaged rectified EMG uV

**Figure 14. Effect of index finger movement tasks upon the components of the cutaneous reflex response recorded from 1DI following digital nerve stimulation of the index finger**

*A,* Cutaneous reflex response recorded from 1DI following stimulation of the digital nerves of the index finger whilst the hand and muscle are relaxed (AT REST). No reflex is elicited. *B,* Cutaneous reflex response from 1DI following stimulation of the digital nerves of the index finger during a light sustained voluntary contraction of 1DI produced by performing abduction/flexion of the index finger (NAT HH). A triphasic cutaneous reflex is evoked consisting of an increase in EMG, E1, followed by a decrease, I1, and followed by a second larger increase in EMG, E2. *C,* cutaneous reflex from 1DI following index finger digital nerve stimulation during random index finger movement and concomitant mental arithmetic (MATHS) and *D,* cutaneous reflex recorded from 1DI during random finger movement (NO ID). In both *C* & *D* the size of the reflex response is unaltered producing E1, I1 and E2 EMG modulations very similar to *A. E,* cutaneous reflex recorded from 1DI following digital nerve stimulations during letter searching (ID) and *F,* during index finger tapping (TAP). In both cases the size of the E2 and I1 reflex components are reduced. The size of E1 is unaltered during both tasks. *A-F* shows the averaged rectified EMG time locked to each stimulus, presented at 5s$^{-1}$. 250 sweeps. All recorded in the same session.

identify letters (ID) when compared with the reflex response obtained during a sustained light abduction/flexion (NAT HH) of the index finger (rmANOVA, $P < 0.05$ in each case). During the random index finger movement task (NO ID) and random index finger movement task with concomitant mental arithmetic (MATHS), the mean size of the E2 and I1 reflex components are slightly reduced but when the difference is compared to the abduction/flexion index finger movement there are no significant differences (rmANOVA, $P > 0.05$ in each case).



| | NAT HH | MATHS | NO ID | ID | TAP |
|---|---|---|---|---|---|
| □ Mean E1 | 7.2 | 3.7 | 4.4 | 4.1 | 4.6 |
| □ Mean I1 | 16.2 | 11.9 | 13.3 | 8 | 9.2 |
| ■ Mean E2 | 22.4 | 18.7 | 16.2 | 8.2 | 12.3 |

**Figure 15. Mean data (+/- 1 S.E.M) obtained from all subjects showing the effect of each task upon the components of the CMR**

Mean size of each component given in table below chart. Reflex response recorded from 1DI following digital nerve stimulation of the index finger during a sustained voluntary abduction/flexion of the index finger (NAT HH) contrasting with the reflex response obtained during random index finger movement and concomitant mental arithmetic (MATHS), during random index finger movement (NO ID), during letter identification using the index finger (ID) and tapping of the index finger (TAP). Grey filled bars: mean size of the E1 reflex component. White filled bars: mean size of the I1 reflex component. Red filled bars: mean size of the E2 reflex response. Significant differences are denoted on the chart *.

The mean size of the E1 reflex response although reduced during all finger movement tasks is not significantly different when compared to the sustained index finger abduction/flexion task (rmANOVA, $P > 0.05$ in each case).

Stimulation of the digital nerves of the index finger failed to elicit a reflex response during the resting task when the hand was relaxed and resting still in all subjects.

The effect of each index finger movement task upon the simultaneously recorded index finger digital nerve SEP recorded from the contralateral sensory cortex is shown in figure 16. The digital SEP recorded during a light sustained abduction/flexion of the index finger (NAT HH) elicits a clear negative up going wave, N20 followed by a decreasing wave, P25. The N20/P25 SEP component measured 3.1µV peak-to-peak, the N20 SEP component peak amplitude measured 2.5µV, and the peak amplitude of the P25 SEP component measured 0.6µV (Fig.16*B*). This is similarly the case when digital nerve SEP is obtained whilst the index finger is relaxed and resting still (AT REST). The size of the peak-to-peak amplitude of the N20/P25 SEP components measured 2.9µV and the peak amplitude of the N20 and P25 SEP components measured 2.1µV and 0.8µV respectively (Fig.16*A*). Conversely, when the index finger performs the tapping (TAP) or random finger movement (NO ID) task the size of the N20/P25 and N20 SEP components are reduced. The peak-to-peak amplitude of the N20/P25 SEP components measured 1.8µV during index finger tapping (Fig.16*F*) and 2.0µV during random finger movement (Fig. 16*D*). The peak amplitude of the N20 SEP component measured 0.9µV during tapping and 1.1µV during random finger movement. The P25 SEP component did not appear to be greatly altered during index finger tapping or the random finger movement task, the peak amplitude measured 0.9µV and 0.9µV respectively. However, when the index finger is engaged in the task requiring identification of

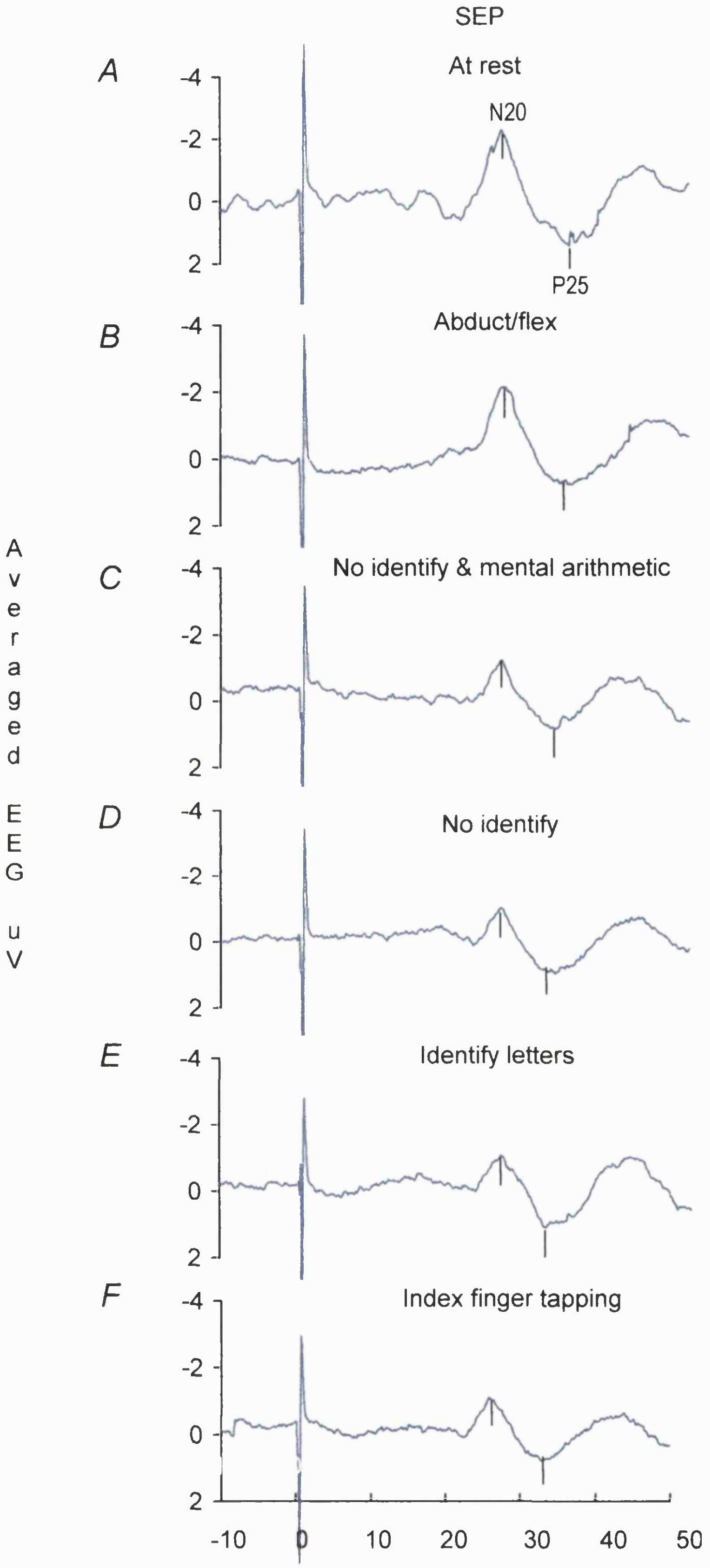
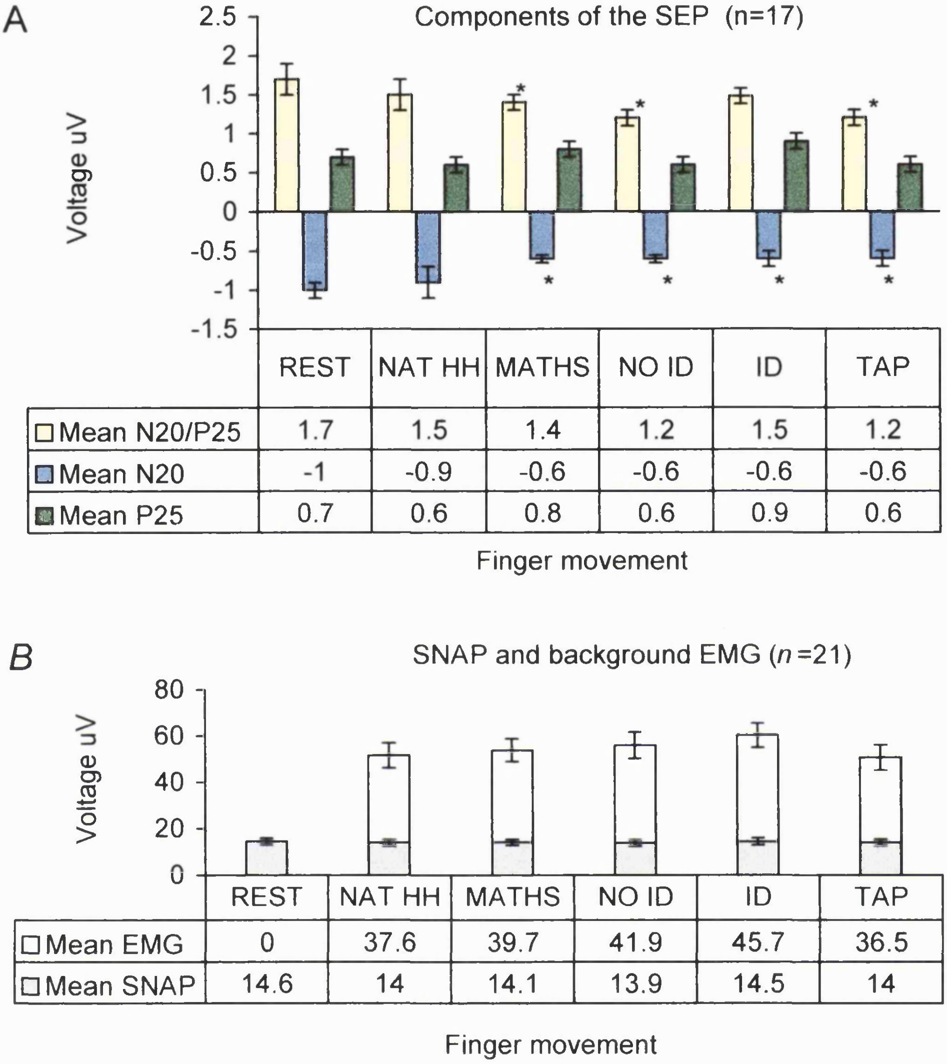

SEP
A
At rest
N20
P25
B
Abduct/flex
C
No identify & mental arithmetic
D
No identify
E
Identify letters
F
Index finger tapping
-4
-2
0
2
-10
0
10
20
30
40
50
Time ms
Averaged EEG uV

**Figure 16. Effect of index finger movement tasks upon the components of the SEP recorded from the contralateral sensory cortex following digital nerve stimulation of the index finger**

*A*, SEP following stimulation of the index finger whilst relaxed & resting still (AT REST). *B,* SEP during a light sustained voluntary contraction of 1DI produced by performing abduction/flexion of the index finger (NAT HH). *C-E,* SEP following index finger digital nerve stimulation during *C,* random index finger movement and concomitant mental arithmetic (MATHS) *D,* during random index finger movement (NO ID), *E,* during letter identification using the index finger (ID) and *F,* during index finger tapping (TAP). Both *A* & *B* evoked a similar SEP consisting of a negative rising potential, N20, followed by a decrease, P25. *C-F,* all tasks reduce the size of the N20/P25 and N20 SEP components. The size of the P25 SEP components increase during the index finger task requiring letter identification (ID) and random finger movement with concomitant mental arithmetic (MATHS). *A-F* shows the averaged EEG time locked to each stimulus, presented at $5s^{-1}$. 250 sweeps. All recorded in the same session.

letters (ID) or random finger movement with concomitant mental arithmetic (MATHS) the size over the N20/P25 and N20 SEP components are reduced, the peak -to-peak amplitude of the N20/P25 SEP component measured 2.1µV and 2.1µV respectively and the peak amplitude of the N20 SEP component measured 0.7µV and 1.0µV respectively. In both cases, the size of the P25 SEP component appears to slightly increase in size, the peak amplitude measured 1.4µV and 1.1µV respectively (Fig.16*C & E)*.

Combining the data obtained from all subjects (4 subjects were excluded because the SEP could not be measured) reveals that the mean size of the N20/P25 SEP components is significantly reduced during index finger tapping (TAP), random index finger movement (NO ID), and random index finger movement with concomitant mental arithmetic (MATHS) when compared to the mean size of the N20/P25 SEP component obtained whilst the finger is relaxed and resting still (rmANOVA, $P < 0.05$ in each case). In contrast, the mean size of the N20/P25 SEP components obtained during the sustained abduction/flexion of the index finger (NAT HH) or searching with the index finger task (ID) is not significantly different when compared to the mean size of the N20/P25 SEP components obtained whilst relaxed and resting still (rmANOVA, $P > 0.05$ in each case). The mean size of the N20 SEP component is significantly reduced during index finger tapping (TAP), random finger movement (NO ID), random finger movement and concomitant mental arithmetic (MATHS) and letter identification using the index finger (ID) when compared to the mean size of the N20 SEP component obtained whilst the hand was relaxed and still (rmANOVA, $P < 0.05$ in each case). With exception, the mean size of the N20 SEP component obtained during a sustained light abduction/flexion of the index finger is not significantly different when compared to the N20 SEP obtained whilst the hand was relaxed and still (rmANOVA, $P > 0.05$). The mean size of the P25 SEP obtained during each index finger movement task was not significantly different when compared to the mean P25 SEP component obtained whilst the hand was relaxed and still (rmANOVA, $P > 0.05$ in each case). This is illustrated in figure 17*A*.



| | REST | NAT HH | MATHS | NO ID | ID | TAP |
|---|---|---|---|---|---|---|
| 🟨 Mean N20/P25 | 1.7 | 1.5 | 1.4 | 1.2 | 1.5 | 1.2 |
| 🟦 Mean N20 | -1 | -0.9 | -0.6 | -0.6 | -0.6 | -0.6 |
| 🟩 Mean P25 | 0.7 | 0.6 | 0.8 | 0.6 | 0.9 | 0.6 |

| | REST | NAT HH | MATHS | NO ID | ID | TAP |
|---|---|---|---|---|---|---|
| □ Mean EMG | 0 | 37.6 | 39.7 | 41.9 | 45.7 | 36.5 |
| □ Mean SNAP | 14.6 | 14 | 14.1 | 13.9 | 14.5 | 14 |

**Figure 17. Mean data (+/- 1 S.E.M) obtained from all subjects showing the effect of different index finger movement tasks upon the components of the SEP, SNAP and background EMG**

Mean size of each response is shown in the table below & +/- 1S.E.M shown on chart. *A,* Components of the SEP recorded from the contralateral sensory cortex following digital nerve stimulation whilst relaxed & resting (AT REST), during a sustained light voluntary abduction/flexion of the index finger (NAT HH), during random index finger movement with concomitant mental arithmetic (MATHS), during random index finger movement (NO ID), during letter identification using the index finger (ID) and during tapping of the index finger (TAP). Yellow filled bars: mean size of the N20/P25 peak-to-peak amplitude uV. Blue filled bars: mean size of the N20 peak amplitude uV. Green filled bars: mean size of the P25 peak amplitude uV. Significant differences found on comparing the components of the SEP obtained during different finger movement tasks with the SEP components recorded whilst relaxed & resting are denoted *. *B,* SNAP & Background EMG during each task described in *A*. White filled bars: background EMG. Grey filled bars: SNAP.

A decrease in the level of perception to the electrical stimulus applied to the index finger was noted in 66% (14/21) of the subjects during one or more of the index finger movement tasks, despite the stimulus remaining constant. Of all index finger movement tasks, index finger tapping was consistently found to be the most difficult task to perform with 48% (10/21) finding it difficult to maintain a constant uniform tapping motion.

The size of the SNAP recorded from the median nerve overlying the wrist (Fig.17*B*) is unaltered during the index finger movement tasks (rmANOVA,$P > 0.05$ in each case).

Background EMG levels during finger movement tasks involving greater levels of movement produced the highest levels of background EMG, however there were no significant differences found when the mean background EMG produced during each muscle task was compared to the mean EMG produced during a light sustained abduction/flexion of the index finger (rmANOVA, $P > 0.05$ in each case). Illustrated in Fig.17*B*.

The variation in the pattern of EMG activity generated during each index finger task in a single subject is shown in Figure 18. It can be seen that the background EMG produced during the light sustained abduction/flexion of the index (NAT HH) and random index finger movement with concomitant mental arithmetic (MATHS) tasks are both relatively constant with little fluctuation in the EMG level. On the other hand, when the random index finger movement (NO ID), identify letters using the index finger (ID) or index finger tapping tasks (TAP) are performed the EMG pattern is much more burst-like and phasic in appearance rather than constant. Because the EMG activity is more phasic during these tasks it is possible that individual sweeps included into the final average may have little or no EMG activities, it is possible that such sweeps could have an influence upon the size of the reflex components recorded during these tasks.

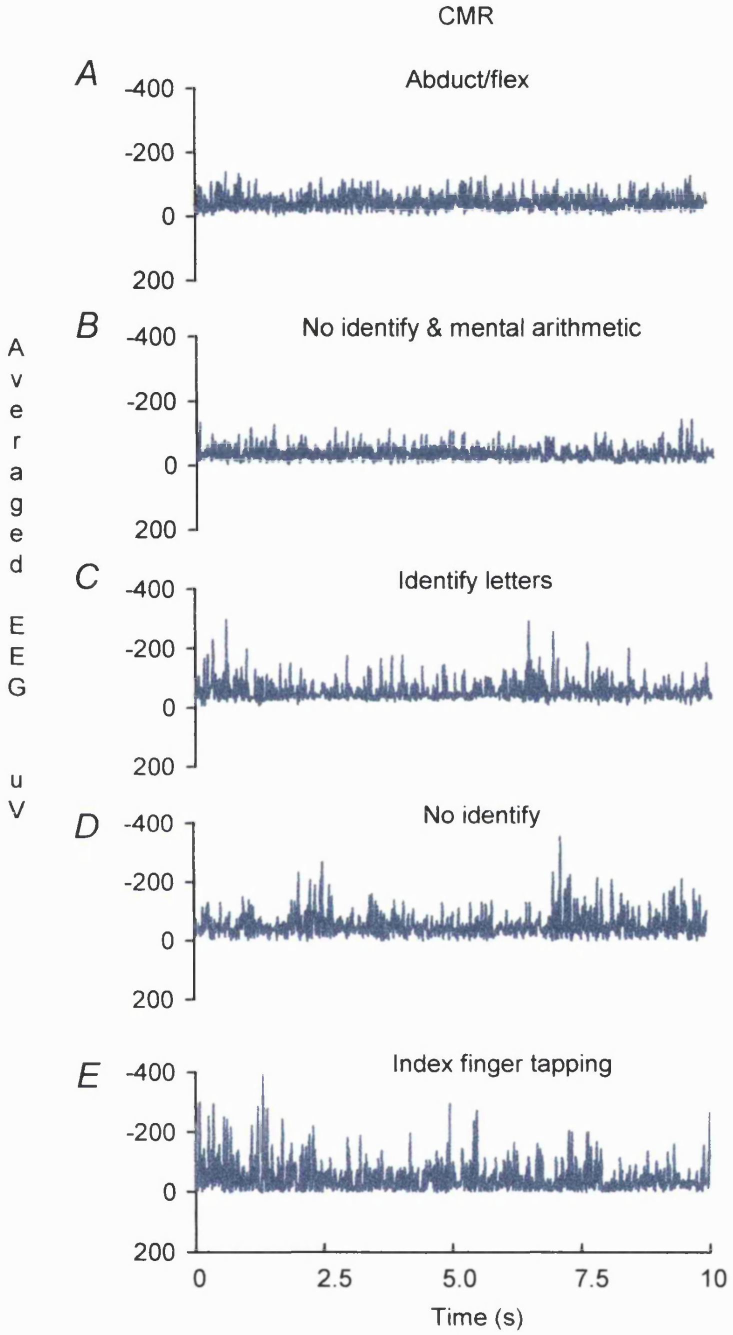


**Figure 18. Background EMG recorded during each of the index finger movement tasks**

Background EMG recorded during *A*, a sustained light index finger abduction/flexion (NAT HH), *B*, random index finger movement and concomitant mental arithmetic (MATHS), *C*, random index finger movement (NO ID), *D*, letter identification using the index finger (ID), *E*, tapping of the index finger (TAP). *A-E* shows a single sweep recorded over 10 seconds.

To exclude this possibility, the pattern of the EMG activity produced when using the index finger to identify letters (ID) or random index finger movement (NO ID) was examined. Each sweep constituting the final 250 sweep average (i) was reviewed and any sweep containing little or no EMG was excluded, thus resulting in a second average in which the sweeps with little or no EMG had been selectively removed (ii). Subsequently the size of the I1 and E2 reflex components from the final 250 average (i) and the second average (ii) were measured, expressed as % EMG modulations and then compared using a t-test. It was found that there was no significant difference in the size of the I1 and E2 reflex components on comparing the % EMG modulations measured from the final 250 average (i) with the second average (ii) (unpaired t-test, $n = 6$, I1, $P = 0.263$; E2, $P = 0.332$).

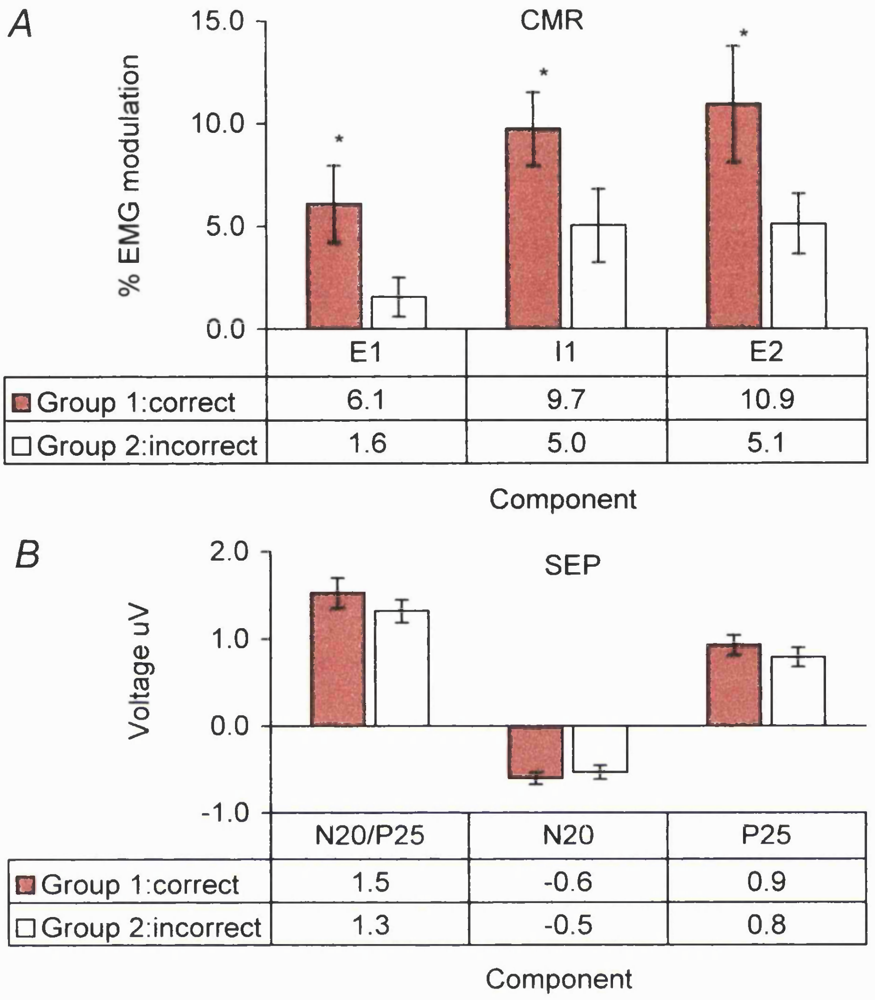
Comparing the reflex and digital nerve SEP components obtained when the index finger is used to identify letters (ID) with the similar task in which the subject performs random index finger task without the need to identify (NO ID) reveals a number of significant differences. Firstly the mean size of the E2 and I1 reflex components are significantly reduced during the identification task when compared to the random finger movement task without the need to identify (rmANOVA, $P < 0.05$ in both cases). Secondly the mean size of the P25 is significantly greater during the identification task (ID) compared to the random finger movement task (NO ID) (rmANOVA, $P < 0.05$). The size of the E1 reflex component, N20/P25 and N20 SEP components, SNAP and background EMG obtained during random index finger movement without identification (NO ID) are not significantly different when compared to the values obtained during the letter identification task (ID) (rmANOVA, $P > 0.05$ in all cases).

The correct or incorrect identification of a letter shape during the index finger letter identification task (ID) was scored for each subject. Of the 17 subjects, 47% (8/17) identified all letter shapes correctly (group 1:*correct*) whilst the remaining 53% (9/17) failed to correctly identify all of the letter shapes cut out into the foam grid (group 2:*incorrect*). The recorded correct scores of group 2:*incorrect* ranged from 12.5-75% (4 subjects were excluded because the SEP could not be measured).

The mean size of E1, I1 and E2 reflex components from subjects that correctly identified all letters (group 1:*correct*) is significantly greater when compared to the mean size of each of the reflex components recorded from subjects that incorrectly identified letters (group 2:*incorrect*) (unpaired t-test, E1, $P = 0.021$; I1, $P = 0.041$; E2, $P = 0.047$). In contrast the mean size of the N20, P25 and N20/P25 SEP components of group 1:*correct* are not significantly different when compared to the mean size of each of the SEP components of group 2:*incorrect* (unpaired t-test, N20, $P = 0.102$; P25, $P = 0.201$; N20/P25, $P = 0.157$). These findings are shown in Figure 19.

Both groups identified similar numbers of letter shapes during the identification task. The mean number of letters identified by subjects was 4.3 for group 1:*correct* and 3.7 for group 2:*incorrect*. The mean number of letters identified by the subjects of group 1:*correct* is not significantly different when compared to the mean number of letters identified by the subjects of group 2:*incorrect* (unpaired t-test, $P = 0.174$).

Each index finger movement task was performed twice in the same recording session; the number of letter shapes correctly identified on the first acquisition was compared with the number correctly identified on the second occasion for each subject. It was found that there was no significant difference between the number of letter shapes correctly scored in the first and second acquisition for the subjects of group 1:*correct* or for the subjects of group 2:*incorrect* (unpaired t-test, group 1:*correct*, $P = 0.701$; group 2:*incorrect*, $P = 0.456$).



| | E1 | I1 | E2 |
|---|---|---|---|
| 🟥 Group 1:correct | 6.1 | 9.7 | 10.9 |
| □ Group 2:incorrect | 1.6 | 5.0 | 5.1 |

| | N20/P25 | N20 | P25 |
|---|---|---|---|
| 🟥 Group 1:correct | 1.5 | -0.6 | 0.9 |
| □ Group 2:incorrect | 1.3 | -0.5 | 0.8 |

**Figure 19. Mean data (+/- 1 S.E.M) obtained from all subjects that correctly identified all letter shapes using the index finger *(group 1:correct)* compared with the mean data from all subjects that did not correctly identify all of the letter shapes using the index finger (group 2:*incorrect)***

Mean size of each response is shown in table below chart and +/- 1 S.E.M is shown on chart. *A*, Components of the reflex recorded from 1DI following electrical stimulation of the digital nerves of the index finger during the letter identification task using the index finger (ID) for all subjects that correctly identified all letter shapes correctly (group 1:*correct*) compared with all subjects which did not correctly identify all letter shapes correctly (group 2:*incorrect*). Filled bars: group 1:*correct*. White bars: group 2:*incorrect*. Significant differences between each group are denoted *. *B*, Components of the SEP simultaneously recorded from the contralateral sensory cortex following digital nerve stimulation of the index finger during the letter identification task using the index finger for group 1:*correct* and group 2:*incorrect* as described in *A*. Filled bars: group 1:*correct*. White bars: group2: *incorrect*.

## Discussion

The present study has shown that the size of the E2 and I1 components of the reflex response recorded from 1DI are reduced during the index finger identification (ID) and index finger tapping (TAP) tasks. In contrast the size of the E2 and I1 components were found to be unaltered during the random index finger movement without identification (No ID) and random index finger movement with concomitant mental arithmetic (MATHS) tasks. The size of the N20/P25 SEP components were found to be reduced in all index finger movement tasks except during the index finger identification and sustained index finger abduction/flexion (NAT HH) task in which the size of the response was found to be unaltered in the present study. The size of the N20 SEP component reflecting activities within areas 3b was reduced during all index finger tasks except during a sustained light abduction/flexion of the index finger (NAT HH) during which the N20 SEP component was found to be unaltered. The size of the E1 component of the reflex response and the P25 SEP component reflecting activities in area 1 was found to be independent of all index finger movement tasks.

In addition a comparison of the index finger identification (ID) and random index finger movement without identification (NO ID) tasks was performed in the present study. It was revealed that the size of the E2 and I1 reflex components obtained during the index finger identification task were smaller, whilst the size of the P25 SEP was greater when compared to the size of the reflex and SEP components obtained during random index finger movement without identification. The size of the N20/P25, N20 SEP and E1 reflex component when both tasks were compared were found to be similar. It has also been shown that the size of the reflex components in the subjects that correctly identified all letters (group 1:*correct)* during the index finger identification (ID) task are greater than the size of the reflex components recorded from the subjects that did not correctly identify all letters (group 2:*incorrect)* during the identification task. The size of the N20/P25, N20 and P25 SEP components were not significantly different when group 1:*correct* and group 2:*incorrect* were compared.

*Index finger tasks*

The tasks employed in the present study were chosen because they all involved using the 1DI muscle to varying degrees. Although all tasks were considered to be forms of precision movement, some movement tasks such as abduction/flexion of the index finger were considered to be relatively simple and isolated in nature whereas other tasks such as the random index finger movement task were considered much more complex requiring the synergistic involvement of intrinsic and extrinsic hand muscles and the index finger identification task which additionally required the subject to pay attention. Interestingly the task which subjects found most difficult was the index finger tapping task. Almost half of the subjects found it difficult to maintain a constant tapping motion of the index finger. This task often required a lot of concentration on the part of the subject, and often subjects would naturally vary the speed of tapping during the acquisition period.

*Changes in afferent volley to the CNS*

The size of the SNAP recorded from the median nerve at the wrist following index finger digital nerve stimulation was not significantly altered during any of the index finger movement tasks. This finding excludes the possibility that any reported changes in the CMR and SEP components during the index finger movement tasks resulted from a change of the afferent information to the spinal cord.

Whilst it was likely that the pattern of background cutaneous and proprioceptor activation altered during each of the index finger movement tasks it is unlikely that differences in background afferent activities account for the reported changes, as the present study found that even when two tasks were performed that were likely to have a similar pattern of background afferent activity, each task had very different effects upon the components of the CMR and SEP. This suggests that changes in the background afferent activities generated during each of the index finger movements is not related to the reported changes in the CMR and SEP in the present study. This concurs with a study by Evans *et al.* 1989 in which it was similarly concluded that background afferent information was not producing a task-dependent change in the CMR (Evans *et al.* 1989).

### *Background EMG*

Overall the mean level of background EMG showed some small levels of fluctuation during the index finger tasks in the present study. Typically index finger movement tasks involving greater levels of movement had the highest background EMG levels, however none of the index finger movement tasks significantly altered the mean background EMG. This excludes the possibility that variations in the background EMG during each of the index finger movement tasks presently reported caused the reduction in the size of the CMR components.

The present study also observed that EMG background patterns recorded from 1DI varied according to the finger movement tasks. This concurs with a study by Flament et al. 1993, which showed that the intramuscular EMG and motor unit responses recorded from 1DI varied during different hand movement tasks despite each subject maintaining the background EMG from 1DI at a constant level.  It is possible that the variation in the pattern of the EMG observed in the present findings reflect the varying degrees of involvement of the 1DI muscle during each of the index finger tasks. If this were simply the case, then it would be expected that the pattern of EMG recorded during random index finger movement with concomitant mental arithmetic (MATHS) should be similar to the EMG pattern observed during random index finger movement without identification (NO ID). This was not found to be the case in the present study, random index finger movement with concomitant mental arithmetic produced a relative constant pattern of EMG activity whilst during random index finger movement without identification the EMG pattern was much more burst-like in appearance.

Alternatively, it is possible to suggest that the pattern of the EMG activity produced during each index finger movement task may in part reflect changes produced within the higher centres of the brain. Support for this suggestion comes from work using monkeys by Lemon *et al.* 1990. Recording from a cortico-motoneurone (CM) cell in the motor cortex, the study found that although the same CM cell was excited during 2 different types of task involving precise finger movements, the pattern of the CM cell activity produced during each movement was very different (Lemon *et al.* 1990). This suggestion is further supported by recent studies using monkeys that have shown that a particular finger movement is encoded in M1 by the pattern of activity of specific groups of CM cells that may be involved in the production of several movements and may be widely distributed throughout the motor cortex (Georgopoulos *et al.* 1999).

It is also possible that the motor unit population changed during each of the different index finger tasks however this is unlikely, as previous studies have shown that similar populations of motor units in 1DI are recruited during different movement tasks (Thomas *et al.* 1986; Evans, 1992; Jones *et al.* 1994). This could be further investigated by comparing the shapes of the motor unit potentials for the 1DI muscle to see if the same motor units were present during each of the different index finger movement tasks.

EMG patterns which appeared to be more phasic and burst–like such as the EMG pattern generated during random index finger movement (NO ID) did not significantly influence the size of the reflex components measured in the present study. Thus excluding the possibility that the individual sweeps with little or no EMG may have produced an artificial reduction in the size of the I1 and E2 reflex components measured in the final average.

### *Index finger movement and the 'gating' effect*

The present study found that there was a generalised reduction in the reflex and SEP components during all of the index finger movement tasks. In addition to this generalised reduction, a number of changes were observed in the supra-spinal reflex components and SEP, which varied according to the nature of the task. The effects and possible explanations for the task dependent changes in the supra-spinal reflex components and SEP are discussed in the following sections.

### *E1 component of the CMR & index finger movement tasks*

The mean size of the E1 component although reduced was not significantly altered during the index finger movement tasks. Given that the E1 reflex component is considered to be spinal in origin (Jenner & Stephens, 1982), the present finding suggests that any change in the CMR and SEP components must have occurred at a level above the spinal cord.

*I1 & E2 reflex and N20/P25 & N20 SEP components & index finger movement tasks*

The present study found that the size of the N20/P25 & N20 components of the SEP were unaltered during a sustained abduction/flexion of the index finger. This finding is in accordance with studies that have similarly shown that the components of the SEP are not modulated during a sustained isometric hold (Rushton *et al.* 1981; Dimitrov*et al.* 1989). It suggests that the afferent information generated by the sustained abduction/flexion of the index finger is regulated in an almost automatic fashion requiring little contribution from the CNS, reflected by no change in the size of the components of the SEP generated by the electrical stimulation of the digital nerves of the index finger.

Tapping of the index finger produced a reduction in the size of the E2 CMR and N20/P25 SEP components in the present study. Similar findings have found that the long latency reflex component of the stretch reflex evoked from the thumb flexor is depressed during finger movement (Wallace & Miles, 1997). It was also found that the size of the I1 reflex component was significantly reduced during index finger tapping. On first inspection it seems that there is a disparity between the findings of the present results and those described in section 1, but this can be reconciled by considering the following facts. Firstly, during the index finger tapping task there was no visual feed back of the EMG. This meant that the subjects did not have to concentrate on maintaining index finger abduction at 10-20% MVC as background EMG levels were monitored by the experimenter. Secondly, subjects simply tapped the index finger rather than abducting the index finger at 10-20% MVC whilst simultaneously tapping the index finger. Thirdly, subjects performed a light sustained abduction and flexion of the index finger in place of sustained index finger abduction at 10-20&% MVC. As a result the overall experimental set was different from that performed in section 1. It is therefore not surprising that there is some disparity between the results reported in section 1 and the present study.

The present study also revealed that 48% of the subjects found that index finger tapping the most difficult task to perform, requiring attention to perform the tapping, suggesting that this task more complex rather than simple in nature.

Given that both I1 and E2 reflex components are supraspinal in origin (Mayston *et al.* 1997), these results support the suggestion that the afferent input generated by the electrical stimulation of the digital nerves of the index finger is 'gated' out in favour of the afferent information generated during the index finger tapping task, resulting in a reduction in the size of the CMR and SEP as originally proposed in section 1.

The N20 SEP component reflecting activities in the area 3b of S1 was significantly reduced during the tapping task indicating that 'gating' of the afferent information occurred at the earliest cortical level. Some studies have reported similar reductions in the size of the N20 SEP component evoked by mixed nerve stimulation during exploratory (Knecht *et al.* 1993) and writing tasks (Hoshiyama & Kakigi, 1999) whilst many have found no change in the size of the N20 SEP during movement tasks (Rushton *et al.* 1981; Waberski *et al.* 1999). Another study which investigated the effect of active finger movement on the somatosensory evoked magnetic fields (SEFs) generated following mixed nerve stimulation has shown that the early cortical deflections N20-P20m and P25-N35m reflecting activities generated within area 3b and 1 are significantly reduced during active finger movement (Kakigi *et al.* 1995). Of course, the present findings do not exclude the possibility that the afferent information was 'gated' within the thalamus or brainstem before reaching the 3b area of the cortex. However, recordings obtained directly from the cortical surface of S1 and thalamus suggest that afferent information is 'gated' predominantly at the cortical level with little contribution from the sub-cortical regions (Hsieh *et al.* 1995).

A similar decrease in the size of the I1 and E2 reflex and N20 SEP components were observed during the letter identification task in the present study. It was also found that the size of the N20/P25 components was not reduced during this task. The reason for the disparity between the N20 and N20/P25 components is explained when the size of each individual component is examined. Whilst the N20 decreases, surprisingly the P25 increases during letter identification, so overall the size of the N20/P25 SEP component remains unaltered. Although the P25 was larger during the identification task it was not found to be significantly different when compared to the P25 measured during abduction/flexion of the index finger excluding the possibility that activities within area 1 are increased during letter identification. Overall these findings are comparable to those obtained during the tapping, again suggesting that during this movement the afferent information from the electrical stimulus is 'gated' out in favour of the afferent information generated during the task, reflected as a decrease in the size of the supraspinal components of the reflex.

Unexpectedly, the present study found that the I1 and E2 reflex components were not significantly reduced during the random index finger movement or random index finger movement with concomitant mental arithmetic task, even though the simultaneously recorded N20/P25 & N20 SEP components were significantly reduced. The reduction in the size of the N20 and N20/P25 SEP components suggests that the afferent input generated by the electrical stimulus is 'gated' out in favour of the afferent information generated during the index finger task but it appears that the change in the afferent input arriving at 3b in S1 does not produce any change in the motor pathways.

The present findings therefore suggest that a decrease in the afferent volley evoked by the electrical stimulus cannot be used to explain the changes in the supraspinal components of the reflex response during these tasks.

Evarts & Fromm, 1977 obtained recordings of the motor cortex using microelectrodes in monkeys trained to perform a number of different movement tasks. It was found that simple large ballistic movements suppress the responsiveness of the cortical neurones. Conversely when the monkey was engage in a task requiring small precise movements of the fingers the responsiveness of the cortical neurones actually increased (Evarts & Fromm, 1977). In man studies using magnetic stimulation have shown that M1 is more excitable during index finger abduction than during a power grip (Datta *et al.* 1989). Flament *et al.* 1993 performed similar studies using magnetic stimulation to measure the level of cortical excitability during a number of precision finger movements. It was found that the level of excitability was greater during a single rather than combined finger movement (Flament *et al.* 1993). From this information it would be expected that precise finger movement tasks requiring the subject to pay attention would increase the size of the supraspinal reflex components. It is therefore very surprising that during the index finger movement tasks requiring the subject to pay attention to the movement actually produced a reduction rather than an increase in the size of the supraspinal reflex components in the present study. Therefore changes in the level of excitability do not easily explain the observed changes in the supraspinal reflex components in the present study. This could be further investigated by performing magnetic stimulation on individuals during each index finger task to measure the level of cortical excitability during each task.

Given that the index finger letter identification and random index finger movement tasks are very similar, it is also probable that each task recruited similar groups of CM cells during the movement task. It is therefore unlikely that the reductions seen during the identification and the no change during random index finger movement are explained by differences in the groups of CM cells within M1. It is possible however that the difference in the effect observed during each task is explained by differences in the pattern of the activity of the CM cells. Evidence to support this explanation arises from a study by Lemon *et al.* 1990 showed that some CM cells were excited by 2 different types of task involving precise finger movements. The only difference was that the pattern of the CM cell activity produced was dependent upon the nature of the movement task (Lemon *et al.* 1990).

Another possible explanation for the observed change is that each index finger task is processed differently by the combined interaction of a number of higher centres within the CNS. It is surmised that the afferent input generated by the index finger task arrives at area 3b in S1. It is processed in area 1 and then this information is then relayed to both the M1 and to the pre-motor cortex (PMA) consisting of areas 6, 8 and the SMA in the frontal cortex. In this region the afferent information is used to prepare and plan the movement (Donoghue & Sanes, 1994). The PMA also receives input from the parietal and prefrontal association cortex, both concerned with the higher processing of the index finger movement. The combined result of all these interactions in the PMA resulting from the original afferent input that reached area 3b is then relayed back to the M1 where the CM cells are modulated, possibly by changing the pattern of activity of the CM cells and ultimately the muscle output regulated in a manner dependent upon the nature of the movement task.

Applying this idea to the findings of the study it is suggested that during simple abduction/flexion of the index finger little relevant afferent information is generated during the sustained movement which the CNS requires to maintain the movement thus the afferent information generated by the electrical stimulus is not 'gated' and so the reflex is not reduced. In tasks that do not require the subject to pay attention but require the synergistic action of several muscles it is possible that the PMA provides some input as well as input from S1 altering the pattern of CM cell firing, reflected as no change in the reflex components. On the other hand in tasks that require the subject to pay attention the input from PMA provides a large amount of input as well as from S1 which modifies the pattern of CM cell differently, reflected as a decrease in the reflex components.

### *P25 SEP component and index finger tasks*

The P25 SEP component was unaltered during all index finger movement tasks in the present study. This finding is contrary to many studies that have found that the P25 SEP component reflecting activities generated in area 1 elicited by mixed nerve stimulation at the wrist is reduced during finger movement (Hoshiyama & Kakigi, 1999; Waberski *et al.* 1999; Huttunen & Hömberg, 1991). Of the few studies that have examined the effect of movement upon the SEP elicited following digital nerve stimulation, Tapia *et al.* 1987 found that the size of the P25 (called P27) component elicited by the simultaneous stimulation of the digital nerves of the thumb and index finger decreased during thumb movement (Tapia *et al.* 1987). However the present study examined the SEP following stimulation of the digital nerves of a single finger. The size of the cortical SEP response elicited by digital nerve stimulation of one finger is extremely small compared to the cortical SEP response evoked by mixed nerve stimulation. Therefore it is possible that if there is any effect, it is not large enough to be detected unless very large sample numbers are employed. The aforementioned problems with recording very small potentials following stimulation of a single digit may well be the reason why the P25 although larger during the index finger letter identification was not significantly different when compared to the P25 during a natural hand hold.

### *Comparisons of attentive and non-attentive index finger movement tasks*

The original hypothesis suggested that tasks requiring the subject to pay attention would be processed differently to a task requiring the subject not to attend to the stimulus. This was tested by comparing the reflex response and SEP recorded during the random index finger movement task which did not require the subject to attend (non-attentive task) with the reflex response and SEP obtained during the letter identification task using the index finger which required attention and concentration to identify the letter shapes (attentive task). These tasks were compared because the movement produced and numbers of muscles activated during both tasks were considered to be the same. It was found that the supraspinal I1 and E2 reflex components were reduced during the attentive but not during the non-attentive index finger task. A much more complex picture was evident when the SEP was compared. The main difference was that the P25 SEP component reflecting activities in area 1 was greater during the attention task compared to the no attention task. The N20 component was reduced during both tasks suggesting that the CNS is focused is attending to the afferent information generated during the task rather than the afferent information generated by the electrical stimulus. These findings support the hypothesis that attentive and non-attentive tasks are processed differently within the CNS. Previous studies using functional magnetic resonance imaging (fMRI) to measure the signal change during attentive and non-attentive tasks have shown that both S1 and S2 signals are increased during tasks requiring the subject to pay attention (Mima *et al.* 1998; Johansen-Berg *et al.* 2000). Therefore it is possible that the increase in the size of the P25 component observed in the present study during the identification task reflects effect of attention.

The spinal E1 reflex component was not significantly different when compared which further supports the idea that any change occur above the level of the spinal cord within the subcortical or cortical areas. The N20/P25 component was not significantly different

Another interesting finding of the present study was that the subjects that correctly identified all letter shapes correctly during the task had significantly larger E1, I1 and E2 reflex components when compared to the subjects that failed to correctly identify all letters. This found not to relate to the fact that some individuals rushed during the identification task as each group identified a similar number of letter shapes. It was also found that if a subject identified all of the letter shapes on the first occasion, they would be as good on the second occasion. This was also the case for subjects that did not score all letter shapes correctly. In this manner subjects that were very good at identifying letters on the first occasion would be no better on the second occasion that the task was performed. There is now evidence that the motor cortex is modulated by tasks that require the subject to pay attention. In a recent study using fMRI, Johnanson-Berg & Matthews, 2002, showed that the signal in M1 decreased when subject were distracted from a finger movement task. This finding may explain why the reflex response is larger in subjects that correctly identified all letter shapes. This explanation is further supported by the present observation that found that the SEP components were no different when each group were compared.

## Conclusions

In conclusion the present study has shown a number of task-dependent changes in the I1 and E2 reflex components and the N20 and N20/P25 SEP components. It has also been demonstrated that activities in area 1 of S1 are enhanced during a task which requires the subject to pay attention compared to a similar task that does not require the subject to pay attention. One possible explanation for this finding is that it reflects changes in attention within S1.

# Section 3: Task-dependence of cutaneous reflexes recorded from hand muscles evoked by distant finger stimulation in man

## Summary

1. Cutaneomuscular reflexes and the SNAP have been recorded during two different types of movement task. With ethical approval and informed consent surface EMG recordings were obtained from intrinsic hand muscles of the preferred hand and the SNAP was recorded from the nerve at the wrist following electrical stimulation of a distant digit.

2. Two experiments were performed. In experiment 1, recordings were obtained from the 1DI muscle following electrical stimulation of the digital nerves of the (i) median nerve and (ii) ulnar nerve whilst subjects performed two tasks (a) sustained abduction of the index finger against resistance at 10-20% MVC, and (b) unrestricted spreading of the fingers. In experiment 2, recordings were obtained from the abductor digiti minimi manus (ADM) muscle following electrical stimulation of the digital nerves of the (i) little finger and (ii) index finger whilst subjects performed (a) sustained abduction of the little finger against resistance at 10-20% MVC, and (b) unrestricted spreading of the fingers. Each task was performed on a number of occasions and in a random order.

3. It was found that the E2 component of the reflex elicited by stimulation of the digital nerves of the little finger was present in 1DI in 13% of trials during index finger abduction. In comparison, when subjects performed an unrestricted spreading of the finger it was found that the E2 reflex component was seen in 43% of trials. The mean size of the E2 reflex component was found to be significantly larger during an unrestricted spreading of the fingers compared to the mean size of the E2 reflex compared during a sustained abduction of the index finger (Mann-Whitney test,

*P* = 0.003).

4. Similarly the E2 component of the reflex response elicited by index finger stimulation, during abduction of the little finger was present in ADM in 20% of trials. By contrast, the E2 component of the reflex in ADM was present in 60% of trials when stimuli to the index finger were given during finger spreading. The mean size of the E2 reflex response was found to be significantly larger during an unrestricted spread of the fingers compared to the mean size of the E2 reflex response obtained during a sustained little finger abduction (Mann-Whitney test, *P* = 0.001).

5. The E1 reflex component recorded from 1DI following stimulation of the little finger digital nerves was present during both movement tasks, with 48% of trials producing an E1 during index finger abduction and 46% of trials during the unrestricted finger spread in experiment 1. Similar results were obtained from ADM following stimulation of the digital nerves of the index finger in experiment 2, with 52% of trials producing a E1 component during little finger abduction compared to 68% of trials when subjects performed an unrestricted finger spread. There were no significant differences in the size of the reflex component on comparing the mean size of E1 obtained during each task for either experiment 1 (Mann-Whitney test, *P* = 0.447) or experiment 2 (Mann-Whitney test, *P* = 0.062).

6. The I1 reflex component was found behave in a similar fashion to the E1 component, with I1 being present during both movement tasks. In the first experiment, stimulation of the digital nerves of the little finger produced an I1 component in 22% of trials during index finger abduction and 29% of trials during the unrestricted finger spread. Equally in the second experiment, stimulation of the digital nerves of the index finger

elicited a I1 reflex component from ADM in 32% of trials during little finger abduction compared to 52% of trials during the unrestricted finger spread. No significant differences were found between the mean I1 component obtained during little finger abduction compared the mean I1 obtained during an unrestricted finger spread for experiment 1(Mann-Whitney test, $P = 0.482$) or experiment 2 (Mann-Whitney test, $P = 0.102$).

6. Reflex responses obtained from 1DI whilst electrically stimulating the index finger were found to be independent of the finger movement task (Mann-Whitney test, E1, $P = 0.135$; I1, $P = 0.159$; E2, $P = 0.158$).

8. Similarly reflex responses elicited from ADM following little finger stimulation were found to be independent of the finger movement task (Mann-Whitney test, E1, $P = 0.407$, I1, $P = 0.496$, E2, $P = 0.409$).

9. It is concluded that the E1 and I1 reflex components show the greatest degree of radiation to distant digital nerve stimulation. However the degree of radiation of the E1 and I1 reflex components was found to be unrelated to the task. In contrast the E2 reflex component was found to be task-dependent, with the size of the E2 reflex response being larger and occurring more frequently during the unrestricted finger spread task. The possible explanations for the observed effects are discussed in the present study.

## Introduction

In this section the effect of distant digital nerve stimulation on the reflex response recorded from intrinsic hand muscles during two different tasks is examined.

As clearly demonstrated in the first and second sections of this thesis, the reflex effects of cutaneous stimulation on a given muscle are known to depend upon the task being carried out when the reflex is elicited. The reflex response is also dependent upon the site of the stimulus. For example, in their study of reflex localisation in the hand, Caccia *et al.* (1973) found that, electrical stimulation of the thumb, index, or middle finger produced reflex effects in the abductor pollicis brevis (APB) during abduction of the thumb. Stimulation of the digital nerves of the ring or fifth finger was found to have less of a modulating effect upon APB than the thumb, index or middle finger (Caccia *et al.* 1973). Thus the cutaneous reflexes that can be elicited from individual finger muscles during movement of a single finger exhibit 'local sign', that is the reflex evoked from the muscle being generated by a related cutaneous sensory field (Sherrington, 1906).

With this background in mind, the aim of the present experiments was to determine whether the radiation of the different reflex components of the CMR elicited by stimulating the digital nerves of a distant finger might become more widespread if the hand is involved in a combined finger movement. It is hypothesised that during a task involving the action of several fingers to produce a combined movement such as an unrestricted finger spread, stimulation of the digital nerves of a distant digit may produce a reflex modulation of the EMG in the intrinsic hand muscle not evident when the index finger works in an isolated abduction.

In addition the present experiments described in this section were initially designed to provide a set of control values for the components of the reflex response elicited in 1DI following electrical stimulation of the digital nerves of the little finger during a sustained abduction of the index finger in a number of healthy individuals. These values are used as the control data in part B and are used to compare the effects of a nerve entrapment upon the components of the reflex response.

## Methods

### *Subjects*

Experiments were performed on the preferred hand of 12 subjects (aged 19-58 years, 10 female) in experiment 1 and 5 subjects (aged 21-58 years, 3 female) in experiment 2. All subjects were healthy and free from neurological disease, or peripheral nerve pathology. Informed consent was obtained from all subjects. The study was carried out with local ethical committee approval and the protocols were carried out in accordance to the declaration of Helsinki, 1964.

### *Cutaneous reflexes*

Reflexes were recorded from 1DI in experiment 1 and from ADM in experiment 2. The ongoing muscle activity was recorded in the same manner as described in section 1.

### *Sensory Volleys*

Sensory volleys were recorded from either the median or ulnar nerve over the wrist using self-adhesive surface electrodes as described in section 1.

### *Stimulation of the digital nerves*

The digital nerves of the finger were stimulated via ring electrodes placed either side of the proximal interphalangeal joint as described in section 1.

### *Experimental procedure*

*Experiment 1.* Recordings were obtained from 1DI whilst electrically stimulating the digital nerves of (a) the index finger and (b) the little finger. The subject was instructed to perform either a sustained abduction of the index or to spread the fingers. To maintain a constant contraction between 10-20% of the maximum, a visual aid was provided for the subject (EMG feedback via a root mean square voltmeter). Reflex modulations of the EMG produced in 1DI and sensory nerve volleys for each movement task were recorded on 2 occasions following index finger (to establish the presence of reflex) and on 5 occasions following little finger stimulation in the same recording session. The movement tasks were performed randomly.

*Experiment 2.* In these experiments, designed to be complementary to those in experiment 1, recordings were obtained from ADM following stimulation of the digital nerves of (a) the little finger and (b) the index finger from 5 of the subjects that had participated in the first experiment. The subject was asked either to abduct the little finger or to spread all of the fingers, maintaining a constant contraction between 10-20% of the maximum with a visual aid. The reflex modulations from ADM and the sensory nerve volleys produced during each movement task were recorded randomly on 2 occasions following little finger stimulation (to establish the presence of reflex) and on 5 occasions following index finger stimulation in the same recording session.

### *Analysis*

#### *Cutaneous reflexes*

The mean area percent modulation of each component was measured and calculated for each component for each 250 average as described in section 1.

#### *Sensory volleys*

The size of the SNAP was measured as described in section 1.

### *Statistical analysis of the data*

The normality of the data was established as per section 1. The significance of each task upon the components of the reflex was examined by performing the paired t-test or Mann-Whitney test where appropriate. The level of significance was set at $P < 0.05$.

#### *Type I errors & the Bonferroni adjustment*

In this section the Mann-Whitney and t-tests employed assume that each observation within a group of observations is sampled independently of each other. Failure to observe this assumption can bias the sample group, resulting in an increased risk of a type I error (false positive) occurring. The Bonferroni adjustment can be employed to reduce this risk (Samuels & Witmer, 1999*b*). The procedure is described in detail on pages 94 & 95.

The exact *P* values calculated using t-tests and the Mann-Whitney test have been given in this section. Therefore any reader of the present thesis can perform the Bonferroni adjustment if it is felt that the observations sampled are not sufficiently independent of each other.

## Results

### *A. Control reflexes recorded from 1DI and ADM*

The effect of stimulating the digital nerves of the index finger upon the averaged rectified EMG during a (a) sustained index finger abduction and (b) unrestricted spreading of the fingers in a single subject are shown in figure 20. Stimulation of the digital nerves of the index finger elicits a triphasic response consisting of an initial increase in EMG, E1, followed by a decrease, I1, followed by a second increase, E2 during both movement tasks.

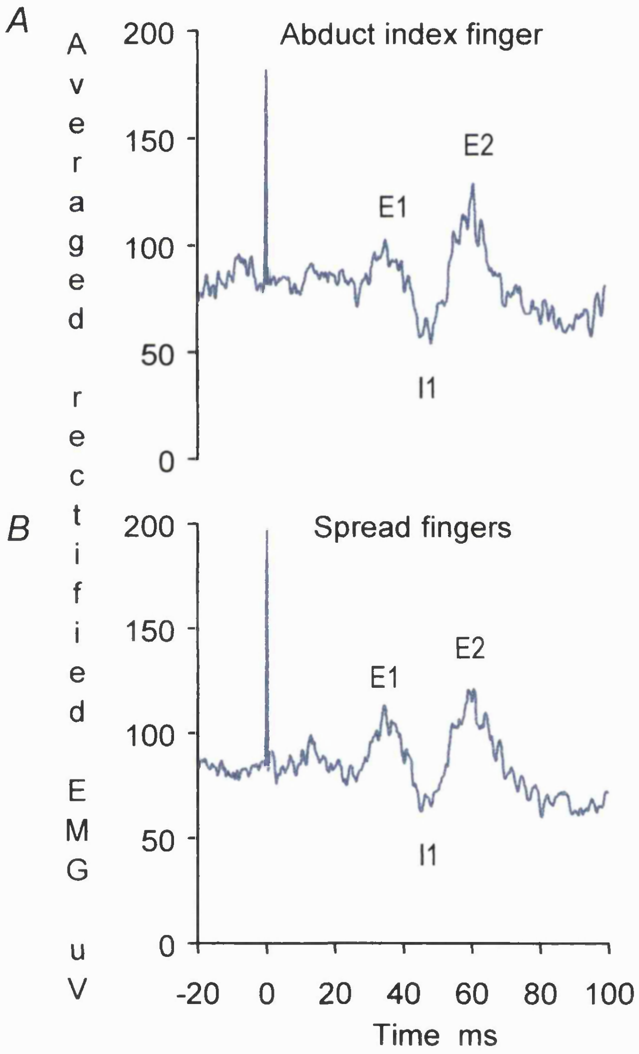


**Figure 20. Effect of (a) index finger abduction and (b) finger spreading upon the reflex response elicited from 1DI following stimulation of the digital nerve of the index finger**

*A,* Reflex response elicited during index finger abduction. *B,* Reflex response elicited during finger spread. *A* & *B*, Both traces elicit a triphasic reflex response consisting of and increase, E1, followed by a decrease, I1, followed by a second increase, E2. Both traces show the averaged rectified EMG time locked to each stimulus, delivered at $5^{-1}$. 250 sweeps.

The E1, I1 & E2 reflex component percent EMG modulations obtained in this subject were 11.4, 26.3 & 25.3 during index finger abduction and 17.7, 25.1 & 30.8 during finger spreading. The SNAP recorded from the median nerve and background EMG measured 13.9µV & 75.5µV respectively during abduction and 13.6µV & 76µV respectively during finger spreading.

Fig. 21 shows recordings obtained from ADM following stimulation of the little finger during a (a) sustained little finger abduction and (b) unrestricted spreading of the fingers in a single individual.

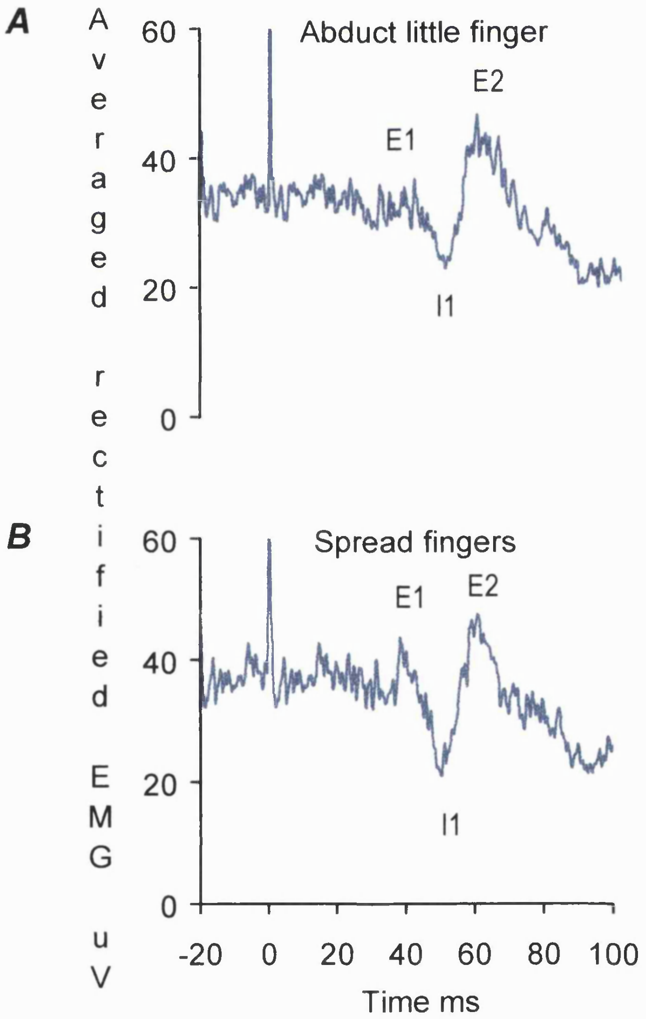


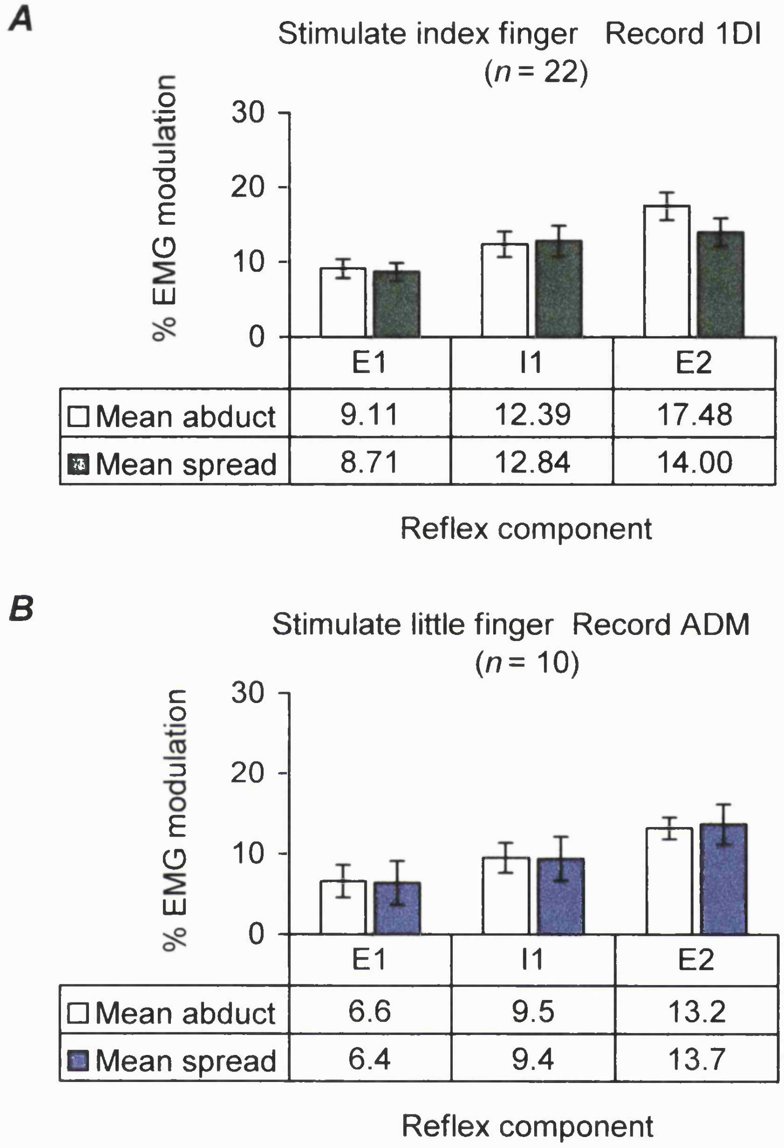
**Figure 21. Effect of (a) little finger abduction and (b) finger spreading upon the reflex response elicited from ADM following stimulation of the digital nerve of the little finger**

*A*, Reflex response elicited during little finger abduction. *B*, Reflex response elicited during finger spread. *A* & *B*, Both traces elicit a triphasic reflex response consisting of and increase, E1, followed by a decrease, I1, followed by a second increase, E2. Both traces show the averaged rectified EMG time locked to each stimulus, delivered at $5^{-1}$. 250 sweeps.

Stimulation of the little finger digital nerves elicits a triphasic reflex modulation of the averaged rectified EMG consisting of an increase, E1, followed by a decrease, I1 and second increase, E2. The percent EMG modulations measured 3.3, 17.2, & 17.4 during little finger abduction and 8.7, 21.0 & 16.2 during finger spreading. The SNAP recorded from the ulnar nerve and background EMG measured 6.0μV & 33μV during abduction and 7.0μV & 34μV during finger spreading.

The combined data recorded from all subjects are illustrated in figure 22 (one subject was excluded because control reflexes could not be recorded). From this data it can be seen that the mean size of each of the reflex components recorded from 1DI (Fig.22*A*) and ADM (fig.22B) during each task is very similar. No significant differences were found in the mean size of the components obtained from 1DI during index finger abduction on comparing with the mean size of each component obtained during the finger spread (paired t-test, *n*=22, E1, *P* = 0.135; I1, *P* = 0.159; E2, *P* = 0.158). Similarly, there were no significant differences in the size of the reflex components recorded from ADM on comparing little finger abduction with finger spreading (paired t-test, *n*=10, E1, *P* = 0.407; I1, *P* = 0.496; E2, *P* = 0.409).

The mean onset latency ± 1 S.E.M recorded from all subjects for the E1 component measured 27.68 ± 1.27, 45.27 ± 1.55 for the I1 component and 55.24 ± 1.58 for the E2 component during index finger abduction. Similarly during finger spread, the mean onset latency ± 1 S.E.M recorded from all subjects for the E1 component measured 27.09 ± 1.00, 43.88 ± 0.80 for the I1 component and 54.60 ± 0.51 for the E2 component. The onset latency of each component obtained during abduction was not significantly different when compared to the onset latency obtained during the finger spreading task (paired t-test, *n*=22, E1, *P* = 0.434; I1, *P* = 0.073, E2, *P* = 0.204).



| | E1 | I1 | E2 |
|---|---|---|---|
| ☐ Mean abduct | 9.11 | 12.39 | 17.48 |
| ■ Mean spread | 8.71 | 12.84 | 14.00 |

| | E1 | I1 | E2 |
|---|---|---|---|
| ☐ Mean abduct | 6.6 | 9.5 | 13.2 |
| ■ Mean spread | 6.4 | 9.4 | 13.7 |

**Figure 22. Mean data +/- 1 S.E.M showing effect of task upon the reflex components elicited from (a) 1DI and (b) ADM following stimulation of the digital nerves**

*A*, reflex components elicited from 1DI following stimulation of the digital nerves of the index finger during index finger abduction and finger spread. (S.E.M values for E1, I1, & E2 were 1.3, 1.6 & 1.6 during abduction and 1.1, 2.0 & 2.0 during spread) *B*, reflex components elicited from ADM following little finger digital nerve stimulation during little finger abduction and finger spread. (S.E.M values for E1, I1, & E2 were 2.1, 1.9 & 1.4 during abduction and 2.7, 2.7 & 2.5 during spread) *A* & *B*, White bars: mean size of each component obtained during abduction. Filled bars: mean size of each component obtained during finger spread.

### *B. Reflexes obtained from 1DI following stimulation of the digital nerves of the little finger*

Fig. 23 shows the effects of stimulating the little finger in one subject on the average rectified EMG recorded from 1DI during a sustained voluntary abduction of the index finger and during an unrestricted spreading of all fingers. During spreading (Fig.23*B*), the stimulus elicits a short latency increase in EMG, E1, followed by a decrease, I1, followed by a second larger increase, E2, producing mean percent modulations of 6.1, 5.8 and 11.1 respectively. In contrast, during an isolated abduction of the index finger (Fig. 23*A*), the same stimulus fails to produce the clear I1 and E2 components elicited during spread. The mean percent modulation

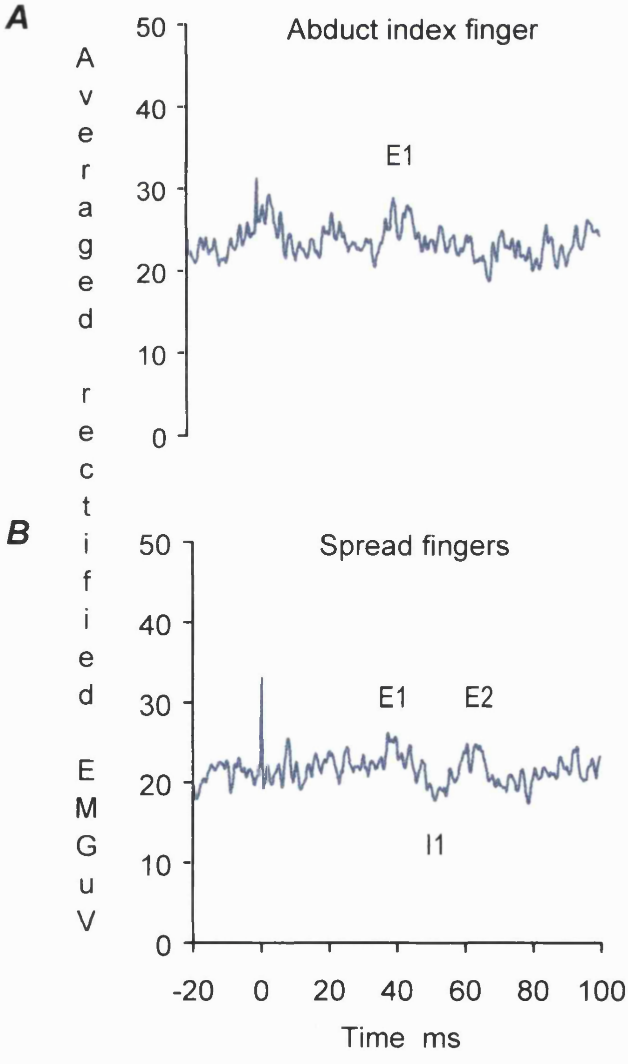


**Figure 23. Effect of index finger abduction compared to unrestricted finger spreading upon the reflex components**

*A & B,* Reflex response recorded from 1DI following stimulation of the little finger digital nerve during *A,* index finger abduction. Stimulation elicits an initial rise in EMG, E1. The later reflex components are absent. *B,* finger spreading. Stimulation elicits a triphasic response consisting of an increase, E1, followed by a decrease, I1, followed by an increase, E2. *A & B,* showed the averaged rectified EMG time locked to each stimulus $5^{-1}$. 250 sweeps.

for the E1 component measured 15.0. The background EMG was 23.0μV during abduction and 21.5μV during spread. The SNAP recorded from the ulnar nerve in these two situations was 4.5 and 4.4 respectively.

The mean data obtained from all of the subjects are summarised in table 1 and illustrated in Fig. 24 (in one subject 4 rather than 5 trials were recorded because of inadequate task performance and signs of fatigue). Taking the data as a whole there is a clear difference in the mean size of the E2 component recorded from 1DI during the index finger abduction and finger spreading tasks. Reflex modulations were evoked from 1DI in 43% of the trials during unrestricted spreading of the fingers compared to 13% of trials during index finger abduction. The difference between the mean percent E2 modulation obtained during abduction compared to the mean percent E2 obtained during finger spreading was significant (Mann-Whitney test, *n=54, P* = 0.003). The mean percent modulations for E1 and I1 during the two tasks were not significantly different (Mann-Whitney test, *n*=54, E1, *P* = 0.447; I1, *P* = 0.482).

***A.* Mean size of reflex components recorded from 1DI following stimulation of the little finger digital nerves during a sustained abduction of the index finger**

| Reflex component (n = 54) | Mean (% modulation) | Standard deviation | Standard error Mean | % reflex responses present |
|---|---|---|---|---|
| E1 | 4.38 | 4.90 | 0.670 | 48.1 |
| I1 | 1.85 | 3.81 | 0.520 | 22.2 |
| E2 | 0.75 | 2.09 | 0.284 | 12.9 |

***B.* Mean size of reflex components recorded from 1Di following stimulation of the little finger digital nerves during a sustained finger spread**

| Reflex component (n = 54) | Mean (% modulation) | Standard deviation | Standard error Mean | % reflex responses present |
|---|---|---|---|---|
| E1 | 4.14 | 4.92 | 0.670 | 46.3 |
| I1 | 2.45 | 4.68 | 0.640 | 29.6 |
| E2 | 3.42 | 4.52 | 0.615 | 42.6* |

**Table 1. Summary of all data obtained from 1DI following little finger digital nerve stimulation during *A*, a sustained abduction of the index finger and *B*, finger spreading. Significant differences denoted***

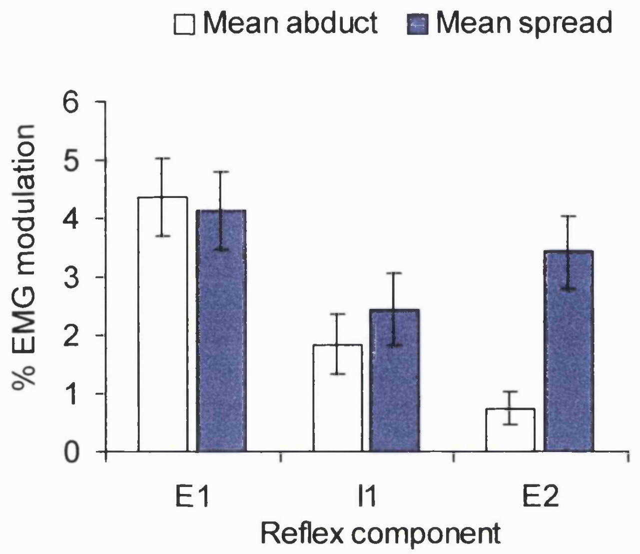


**Figure 24. Mean data +/- 1 S.E.M obtained from 1DI following stimulation of the digital nerves of the little finger during index finger abduction and finger spread**

White filled bars: index finger abduction. Blue filled bars finger spread.

*C. Reflex response elicited from ADM following stimulation of the index finger digital nerve*

The results for the complementary experiment are shown in Fig. 25, which illustrates the effect of stimulating the index finger on the averaged rectified EMG recorded from ADM during sustained abduction of the fifth finger and during a sustained unrestricted spreading of the fingers. In this subject, during spread (Fig. 25*B*) stimulation of the index finger evokes an increase in EMG, E1, followed by a small decrease, I1, and by a second increase, E2. The mean percent area modulations produced were 6.4, 9.5 & 6.8 respectively. However during an isolated abduction of the fifth finger (Fig.25*A*), stimulation of the same finger elicits an initial increase in EMG, E1, followed by a decrease, I1, but fails to evoke the component E2 apparent during spread. The mean percent modulations for E1 and I1 were 6.5 and 6.8 respectively. The background EMG was 23.5μV during abduction, and 22.5μV during spread. The sensory volley recorded from the median nerve on this occasion was 11.0μV and 11.0μV respectively.

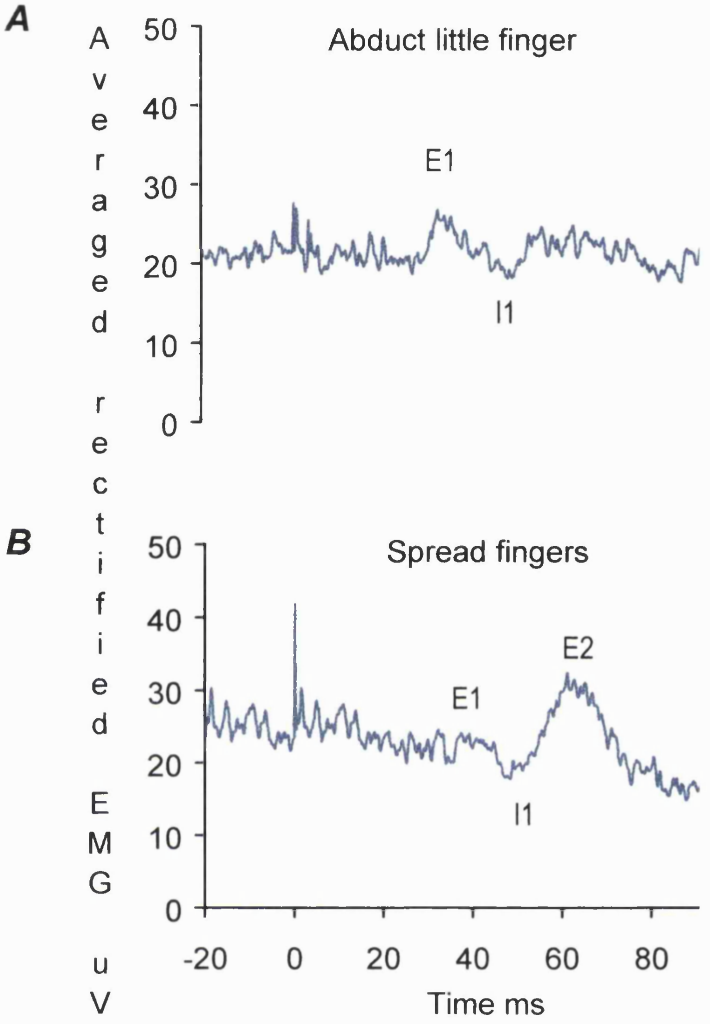


**Figure 25. Effect of index finger digital nerve stimulation upon the reflex response recorded from ADM during a sustained index finger abduction and unrestricted spreading of the fingers**

*A & B,* Reflex response recorded from ADM following stimulation of the index finger digital nerve during *A,* little finger abduction. Stimulation elicits an initial rise in EMG, E1, followed by a decrease, I1. The later reflex component is absent. *B,* finger spreading, stimulation elicits a triphasic response consisting of an increase, E1, followed by a decrease, I1, followed by an increase, E2.

*A & B,* showed the averaged rectified EMG time locked to each stimulus $5^{-1}$. 250 sweeps.

Fig. 26 illustrates and table 2 summarises the results for the complementary experiment. Once again the E2 component of the reflex is affected by the movement task. During finger spreading, stimulation of the index finger produced an E2 component in ADM in 60% of trials compared to 20% during an isolated abduction of the little finger. The mean size of the E2 component recorded during the finger spreading task was significantly larger when compared to the mean size of the E2 component obtained during little finger abduction (Mann-Whitney, $P = 0.001$). The mean percent modulations for E1 and I1 during the two tasks were not significantly different when compared (Mann-Whitney, E1, $P = 0.062$; I1, $P = 0.102$).

***A.*** **Mean size of reflex components recorded from ADM following stimulation of the index finger digital nerves during a sustained abduction of the little finger**

| *Reflex component (n = 25)* | *Mean (% modulation)* | *Standard deviation* | *Standard error mean* | *% reflex responses present* |
|---|---|---|---|---|
| *E1* | *3.03* | *3.66* | *0.726* | *52.0* |
| *I1* | *2.10* | *3.42* | *0.684* | *32.0* |
| *E2* | *0.80* | *1.69* | *0.338* | *20.0* |

***B.*** **Mean size of reflex components recorded from ADM following stimulation of the index finger digital nerves during a sustained finger spread**

| *Reflex component (n = 25)* | *Mean (% modulation)* | *Standard deviation* | *Standard error mean* | *% reflex responses present* |
|---|---|---|---|---|
| *E1* | *5.23* | *4.02* | *0.805* | *68.0* |
| *I1* | *3.76* | *4.11* | *0.822* | *52.0* |
| *E2* | *5.12* | *4.79* | *0.959* | *60.0** |

**Table 2. Summary of all data obtained from ADM following index finger digital nerve stimulation during *A*, a sustained little finger abduction and *B*, finger spreading. Significant differences denoted ***

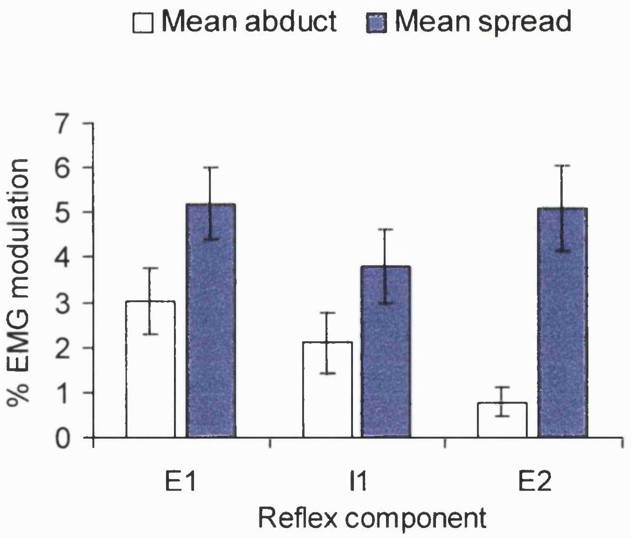


**Figure 26. Mean data +/- 1 S.E.M obtained from ADM following stimulation of the digital nerves of the index finger during little finger abduction and finger spread**

White filled bars: little finger abduction.

Blue filled bars: finger spread.

### *D. Reflex responses recorded from 1DI and ADM to distant and local digital nerve stimulation*

When the data from all subjects were combined it was found that the mean size of the reflex components elicited from 1DI and ADM were largest when stimulating the digital nerves of a finger local to the muscle compared to distant digital nerve stimulation. This is shown in figure 27.

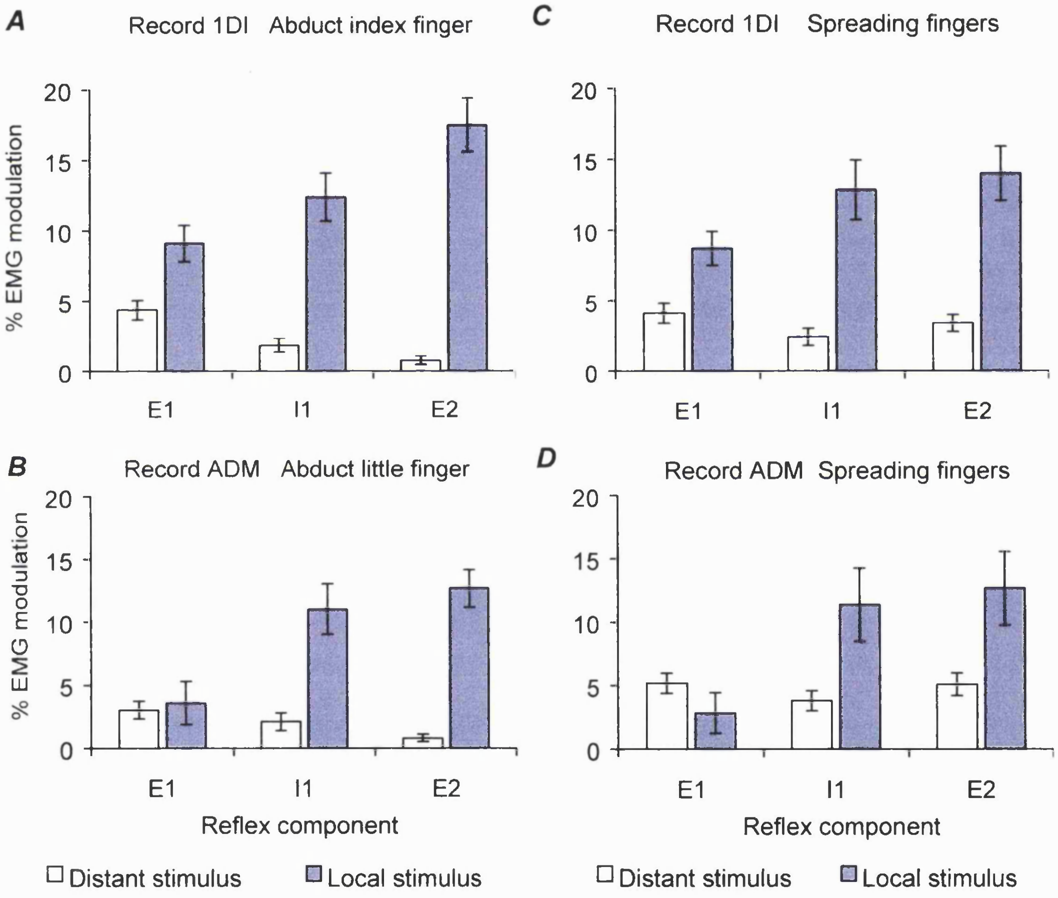


**Figure 27. Effect of stimulus location upon the size of the reflex components recorded from 1DI and ADM during each finger movement task**

*A-D*, Mean data. *A & C*, recording from 1DI during *A*, index finger abduction and *C*, finger spreading. *B & D*, recording from ADM during *B*, little finger abduction and *D*, finger spreading. White filled bars: digital nerve stimulation distant to muscle. Blue filled bars digital nerve stimulation local to muscle.

### *E. Sensory volleys recorded during the tasks*

The mean size of the sensory afferent volley was not significantly altered during any of the tasks recorded from either 1DI or ADM (paired t-test, $P > 0.05$ in each case. The exact $P$ values are stated in table below, see **). These data are summarised in table 3.

**Mean size of the sensory volley recorded from 1DI and ADM during each of the sustained abduction tasks**

| Sensory Volley (uV) | Record 1DI Stimulate index finger | Record 1DI Stimulate little finger | Record ADM Stimulate little finger | Record ADM Stimulate index finger |
|---|---|---|---|---|
| Mean | 13.05 | 7.05 | 8.35 | 8.02 |
| Standard error mean | 0.685 | 0.620 | 0.872 | 0.338 |
| *N* | 22 | 54 | 10 | 25 |

**Mean size of the sensory volley recorded from 1DI and ADM during each of the finger spreading tasks**

| Sensory Volley (uV) | Record 1DI Stimulate index finger | Record 1DI Stimulate little finger | Record ADM Stimulate little finger | Record ADM Stimulate index finger |
|---|---|---|---|---|
| Mean | 14.52 | 6.82 | 7.85 | 7.92 |
| Standard error mean | 0.75 | 0.615 | 0.700 | 0.380 |
| *N* | 22 | 54 | 10 | 25 |

| | | | | |
|---|---|---|---|---|
| *P value* ** | 0.429 | 0.461 | 0.148 | 0.891 |

**Table 3. Summary of all SNAP data obtained during all experiments**

## Discussion

The present study has demonstrated that the reflex effects of stimulating an individual finger radiate more widely to distant intrinsic hand muscles when the muscles of the hand are used during a combined movement of the fingers than when the fingers are used in isolation. This effect is evident for the long latency E2 component of the reflex. In addition, the present study found that E2 task dependence is not evident when the stimulus is moved locally to a digit near the muscle. The E1 and I1 reflex components were unaltered during the finger movement tasks.

### *Afferent volley to CNS*

The present study found that the size of the sensory afferent volley was not significantly different during the abduction or spreading finger tasks. This excludes the possibility that the observed changes in the E2 reflex component are due to a change in the afferent input arriving at the spinal cord.

It is possible that the levels of background activities may have varied between each task. However, it seems unlikely that the present observations are produced by changes in background afferent activities as already discussed in part 1, section 2 because finger movement tasks involving similar amounts of afferent background were found to produce very different effects upon the reflex components elicited by digital nerve stimulation. Evans *et al.* 1989 reported similar findings.

### *Task dependence of the E2 reflex component following distant digital nerve stimulation*

In the present study it was found that the size of the E2 reflex component was larger during a finger spread compared to a simple abduction of the finger when the digital nerves of a distant finger were stimulated. There are a number of mechanisms that may underlie this effect.

Execution of a voluntary motor task is accompanied by activation of a set of corticomotoneuronal (CM) cells in the motor cortex (M1) specific to the performed movement task (Georgopoulos *et al.* 1986; Lemon *et al.* 1998; Georgopoulos *et al.* 1999; Kakei *et al.* 1999). From the present results it appears that the CM cell set activated is provided with a functional or task related sensory accompaniment. In an isolated finger movement, it is possible to suppose that the CM set (or task group) is paired to the reflex input from a single finger. However when involved in a combined movement, the CM set is provided with input combined from different fingers. Direct support for this idea would require observations of changes in CM cell responsiveness to afferent inputs during different finger movement tasks. This has yet to be achieved. But in walking cats, for example, the afferent input received by CM cells in M1 from the forelimb changes as the different components of the step cycle are executed (Marple-Horvat & Armstrong, 1999). Regulation of the afferent input could take place at the level of the dorsal column nuclei (DCN) (Coulter, 1974), ventral posteriolateral nucleus (VPL) in the thalamus (Tsumoto *et al.* 1975), or at the somatosensory cortex (S1) (Kakigi *et al.* 1995).

Recently, Palmeri *et al.* (1999) have shown in semi-chronically implanted cats, that the M1 is able to 'gate' cutaneous information within the somatosensory pathways at the level of the DCN and VPL, resulting in a cutaneous input, which by the simultaneous inhibition of surrounding neurons is either enhanced or depressed. This gating results in a facilitation of a cutaneous input originating from skin around or close to an active area while depressing transmission of any cutaneous input originating from other areas. Thus, by interference, when our subjects produced an isolated abduction of the index finger, activity evoked by stimulation of the digital nerves of the inactive little finger was subject to inhibition as it ascended towards the cortex. In contrast, when the little finger was active, as in the spread task, transmission of the same afferent signal was facilitated.

It is also possible that during the abduction task there is a greater proportion of CM cell activation. Fetz & Cheney (1987) demonstrated that CM cells are more active during a precision rather than a power grip in the monkey. Therefore it is possible to suggest that in the present study, during the abduction task a greater number of CM cells are active, which exert an inhibitory effect on the afferent input to the CM cells making it responsive only to the afferent input from one finger. In contrast when the spreading task is performed the degree of inhibition on the CM cells is reduced, allowing a greater number of CM cells to respond, thus producing the long latency reflex effects reported in the present study.

Another explanation for the findings could be related to differences in the pattern of CM cell activation between both movement tasks performed in the present study. Lemon *et al.* 1990 have demonstrated in the monkey that a proportion of CM cells fire differently when two different precision tasks employing the fingers are performed. Therefore it is possible that during the spreading task a proportion of CM cells become responsive to input from all of the fingers, being unresponsive during the single finger movement.

There is also evidence that CM cells exhibit oscillatory synchronisation in a task dependent manner (Baker *et al.* 1999; Kilner *et al.* 1999; Lemon *et al.* 1998; Baker *et al.* 1997) possibly generated by local cortical circuits. In their studies of a precision grip task, Baker *et* *al.* (1999) found that pyramidal tract neurons oscillated synchronously, during the part of the task that involved the subjects actively maintaining a steady grip. It was not evident at any other stage of the precision grip task (Baker *et al.* 1999). In a parallel way, Bennett & Lemon (1996) have shown that a proportion of CM cells produce a post spike facilitation of EMG in intrinsic hand muscles during independent finger movements (Bennett & Lemon, 1996). Therefore one might suggest that during a single finger movement the CM set involved in that movement acts in a fractionated manner and receives input from the functionally related sensory field from that finger. However when producing a combined movement of all fingers in a syngeristic manner as in the present experiment, it is possible that the firing of different sets of CM cells may be combined together along with their functionally related individual sensory fields in such a way that the relevant cutaneous input to each set plays a part in guiding the combined actions of the muscles involved in generating the desired movement. In this manner, the CM set within M1, along with its sensory inputs organises in a dynamic manner dependent upon the movement performed.

At a more general level we may consider the present findings in relation to the "Sharing Principle" that has been discussed in previous papers (Gibbs *et al.* 1995*a*; Gibbs *et al.* 1995*b*; Stephens *et al.* 2000). In its general form this states that motor neurones innervating muscle pairs that share action about a common joint or shared mechanical axis share common pre-synaptic input. The converse is also true: motor neurones innervating co-contracting muscles that do not share a common action about a common joint or mechanical axis do not share a common input. In the present study we find that sensory inputs that share a function share a reflex effect. When the fingers share a function, as when the fingers are spread, the cutaneous afferents from the different fingers share a reflex effect on the muscles acting on the different fingers. But when the fingers do not, as when a finger is moved independently, these same cutaneous afferents from the different fingers no longer share their reflex effects to the different finger muscles; the afferents from the little finger, no longer produces reflex effects on 1DI when the index finger is moved alone. Thus the "Sharing Principle" in its general form for the sharing of common pre-synaptic inputs between motor neurone pools can be particularised in relation to reflex inputs. Reflex inputs from different sensory fields are shared or bound together when the motor outputs are combined in such a way that the different sensory fields are functionally combined.

### *Possible functional relevance of observed E2 changes*

Considering the present findings in relation to the performance of normal hand movements, it is possible to imagine how it would make physiological sense to receive a combined cutaneous feedback when performing a movement involving all fingers, for example while grasping a cup. In this case, it would be functionally advantageous for the CM cells in the M1 region active during this task to have access to cutaneous input derived from all fingers. This would be expected to contribute to the accuracy of the movement performed. Equally, in the performance of an individual finger movement, it might be functionally disadvantageous for CM cells active during this task to have access to cutaneous input derived from fingers that are not involved. It would advantageous to ignore sensory input from the other fingers, which might otherwise provide functionally irrelevant information.

### *Reflex responses elicited from the muscle to local digital nerve stimulation*

The reflex components elicited following stimulation of the digital nerves of a finger that was local to the muscle was always larger when compared to the reflex components elicited following stimulation of the digital nerves of a distant finger in the present study. These findings demonstrate 'local sign' first described by Sherrington in 1906. Caccia *et al.* (1973) showed that the size of a reflex response elicited from APB was maximal when the thumb or index finger were stimulated (Caccia *et al.* 1973). More recently, Furness & Harper (1998) showed how reflex responsiveness is mostly restricted to muscles that are local to the stimulation site by recording the reflex responses in the intrinsic hand muscles elicited by local and distant digital nerve stimulation in a number of healthy individuals. Recording from 1DI and ADM it was found that if the digital nerves of the index finger were stimulated whilst the index finger elicits a reflex response that is largest in 1DI. They also found that this effect could be reversed if the stimulus was moved to the little finger whilst abducting the little finger (Furness & Harper, 1998).

Of interest in the present study, was the observed lack of task dependence of the E2 component following stimulation of the digital nerves of a finger that was local to the intrinsic hand muscle. These findings suggest that it is the position of the stimulus that is important in producing the task dependent effects observed when the same stimulus is moved to a distant digit.

### *The E1 component*

In the present study, the spinal reflex component E1 was not significantly different during either movement task. However, the E1 component showed the greatest degree of radiation. From this it is concluded that any of the observed changes in the present study occurred at a level above the spinal cord. These findings also suggest that the reflex component E1 is not task dependent during either finger movement task in the present study. It is interesting that the E1 component showed the greatest radiation but no task dependence.

This might be explained by changes in the level of descending inhibition onto the spinal cord produced by the performance of each movement task.

### *The I1 component*

The present study found that the I1 reflex component was not significantly different during the abduction and spreading tasks. Given that a variety of evidence suggests that the I1 component is transcortical, mediated via the dorsal columns, sensorimotor cortex and corticospinal tract (Mayston *et al.* 1997), it is surprising that the I1 component does not behave in a similar fashion to the E2 reflex component. As discusses in part 1, section 2, there is building evidence to suggest that the I1 reflex component behaves differently from the E2 reflex component.

## Conclusions

In conclusion the present study has shown that stimulating a distant finger produces reflex effects that radiate more widely to distant intrinsic hand muscles when the muscles of the hand are used during a combined movement of the fingers than when the fingers are used in isolation. This effect is evident for the long latency E2 component of the reflex. In addition, the present study found that E2 task dependence is not evident when the stimulus is moved locally to a digit near the muscle. The E1 and I1 reflex components were unaltered during the finger movement tasks.

# PART B: Evidence for reflex reorganisation in subjects with a chronic partial nerve entrapment of the median nerve in man

## General Introduction

In part B of the thesis, reflex cutaneomuscular responsiveness to stimulation of the digital nerves of the little finger is investigated in 19 subjects with carpal tunnel syndrome, a chronic partial median nerve entrapment at the wrist (CPNE). Cutaneomuscular responsiveness to digital nerve stimulation of the little finger is also examined in 1 subject with a transection of the median nerve and 1 subject with an index finger amputation.

In prelude to the present experiments this general introduction is divided into two sections. The first section is intended to provide a brief overview of the pathological and clinical features of carpal tunnel syndrome, the second section reviews evidence for reorganisation within different regions of the CNS following injury.

## Chronic partial median nerve entrapment

In the healthy hand the median nerve passes through the carpal tunnel, branching to form the digital nerves, which innervate the thumb, index, middle and medial aspect of the ring finger, whilst the ulnar nerve innervates the lateral side of the ring finger, and little finger. Unlike the median nerve, the ulnar nerve does not pass through the carpal tunnel and is usually unaffected in CTS (Dawson *et al.* 1999).

In carpal tunnel syndrome (CTS) the median nerve is compressed as it passes through the carpal tunnel at the level of the wrist (Marie & Foix, 1913). The median nerve is often partially damaged as it passes through the carpal tunnel, resulting in a loss of the afferents innervating the fingers. This is reflected by a decrease in the amplitude of the sensory action potential recorded from the median nerve at the wrist following electrical stimulation of the digital nerves of the finger. CTS is the most common form of peripheral nerve entrapment (Mühlau *et al.* 1984). Recent population based research suggests that about 3% of the adult population have CTS (Atroshi *et al.* 1999). Patients with CTS are predominantly female (ratio of 3:1) and the age of CTS onset typically ranges from 30 - 50 years of age (Tanaka *et al.* 1994).

The carpal tunnel through which the median nerve and 9 extrinsic finger flexor tendons pass is constructed from 4 carpal bones (Hamate, capitate, trapezoid & trapezium) and sealed by the flexor retinaculum, making the carpal tunnel crowded, rigid and inflexible. Unfortunately the nature of this very tight and crowded arrangement increases the possibility of median nerve entrapment. As a result when the carpal tunnel pressure is measured in subjects with CTS it is significantly higher than when compared to healthy control subjects (Gelberman *et al.* 1981). Also, the cross-sectional area of the carpal tunnel imaged by computer tomography is reduced in subjects with CTS compared to healthy control subjects (Dekel & Coates, 1979).

CTS is associated with a wide range of conditions including, rheumatoid arthritis, simple fractures. Other causes include trauma to the nerve such as the damage associated with a Colles' fracture, ganglia or tumours, endocrine, vitamin deficiencies and pregnancy.

CTS may be caused by intrinsic swelling of the median nerve or by extrinsic compression of the median nerve within the carpal tunnel. The most common cause is non-specific flexor tenosynovitis. In this condition the flexor tenosynovium becomes abnormally thickened, there appears to be little in the way of inflammation rather degeneration as a result of repeated use of the flexors (Fuchs *et al.* 1991).

The clinical features associated in CTS in a single subject were originally described in a short report published by Marie & Foix in 1913. In the report the authors also suggested that the clinical symptoms were produced by compression of the median nerve under the flexor retinaculum (Marie & Foix, 1913).

When chronic compression of the median nerve occurs within the carpal tunnel it produces an impairment of the sensory and/or motor function of the median nerve. Typically patients complain of nocturnal numbness, tingling and painful paraesthesia of the fingers. The distribution of the paraesthesia varies from subject to subject with all or just a few fingers affected. The classical pattern of paraesthesia involves the thumb, index and middle fingers, whilst the ring and little fingers are spared. Other sensory disturbances such as tightness of the fingers and the sensation of having swollen fingers are common. In the early stages of CTS shaking the limb may help to relieve the paraesthesia. When sensation is examined it can very from no change to complete paraesthesia. The subject's 2-point discrimination may be unaffected or reduced when compared to the ulnar nerve. Tinel's or Phalen's sign may be positive or negative. Phalen found Tinel's sign positive in 60% and Phalen's sign positive in 80% of subjects with CTS (Phalen, 1970). The pattern of pain may radiate up to the forearms but this is variable (Dawson *et al.* 1999). In more severe nerve entrapments the sensory disturbance is increased and the fingers can become persistently numb. There may also be atrophy of the thenar muscles may occur making the thumb abduction weaker than normal and there is usually a strong element of nocturnal pain (Dawson *et al.* 1999). Subjects also complain being unable to use their hands, finding tasks that require skilled fine movement such as handwriting or picking up small objects very difficult to perform (Dawson *et al.* 1999).

Nerve conduction studies (NCS) are routinely employed to confirm the clinical diagnosis of CTS by demonstrating a localised conduction slowing across the wrist.

Recordings of the sensory action potential distal to the carpal tunnel are increased in latency (when compared to the sensory action potential elicited from the ulnar nerve) and the conduction velocity is reduced following electrical stimulation of the digital nerves of the finger innervated by the median nerve. Additionally, the amplitude of the sensory potential is decreased or absent. The motor latency recorded from abductor pollicis brevis (APB) across the wrist is not usually delayed until the entrapment is quite marked (Dawson *et al.* 1999). The severity of median nerve entrapment can be graded according to the electrophysiological changes recorded. However there remains a large amount of variation as to how the changes are used to grade the severity of entrapment. Stevens *et al.* 1999 suggested that the severity of entrapment could be divided into three groups denoted mild, moderate, and severe according to the changes in the sensory and motor action potentials (Stevens *et al.* 1999). More recently, Bland (2000) proposed a new system of assessing the severity of the entrapment by dividing the electrophysiological findings into six grades, ranging from very mild to extremely severe (Bland, 2000).

Chronic entrapment damages the peripheral nerve in a number of different ways. The damage is usually dependent upon the severity and duration of entrapment. One such way a peripheral nerve is injured is by damaging the myelin surrounding the nerve axon. If the myelin is completely lost it will cause a conduction block, by which action potentials can be propagated above and below the entrapment but not through the region of myelin loss at the site of entrapment. This type of nerve damage is referred to as neuropraxia (Seddon, 1943). Abnormal widening of the nodes of Ranvier is another way in which the peripheral nerve is damaged by entrapment. This process is defined as Axonstenosis. The propagation of the action potential is not blocked across the area of entrapment but is slowed (Feasby *et al.* 1985). Chronic nerve entrapment can also damage the axons. In axonotmesis, axon continuity is lost but the connective sheath is not damaged and in neurotmesis both axon and connective sheath continuity are lost. Both types of axon damage lead to Wallerian degeneration of the nerve distal to the site of damage. In neuromesis there is a greater chance for re-growth because the Schwann cells make tubules for the axons to grow along, increasing the chance of reinnervation.

Some of the earliest descriptions of the histopathological changes that occur in a chronic entrapment neuropathy were made by Fullerton & Gilliatt in 1967 based upon the observations of a naturally occurring chronic entrapment neuropathy in the hind limb of the guinea pig. From the histological examination of the peripheral nerve at the site of entrapment the study found that axonal conduction was slowed. There was also evidence of segmental demyelination and remyelination and there was some Wallerian degeneration subsequent to axon damage at the entrapment site (Fullerton & Gilliatt, 1967).

Anderson *et al.* (1970) examined chronic entrapment of the median nerve in the guinea pig proximal to the site of entrapment. Concordant with the studies of Fullerton and Gilliatt, 1967, examination of the median nerve at the site of a mild entrapment revealed slowing of axonal conduction. In addition it was found that as the entrapment became more severe there was a decrease in the myelinated fibres, particularly the large diameter fibres and evidence of demyelination and remyelination and axonal damage in the area of entrapment (Anderson *et al.* 1970).

At about the same time a number of studies began to report the histopathological changes of a chronic nerve entrapment in man. The most common chronic entrapment in man occurs at the wrist involving the median nerve, commonly known as carpal tunnel syndrome (CTS). Thomas & Fullerton (1963) reported the pathophysiological findings in an individual with clinically diagnosed CTS prior to death (patient diagnosed with tumour). Histological examination of the median nerve revealed similar changes to the findings in animals. There was clear evidence of demyelination and remyelination. There was also evidence of axonal degeneration without any evidence for the selective damage to any particular class of axon and swelling proximal to the site of entrapment.

Later, Brown *et al.* (1976) found evidence of conduction slowing which occurred either just proximal or distal to the site of entrapment in subjects that were undergoing surgical decompression of the median nerve at the wrist. They also found thickening of the fibrous tissues, scarring/adhesions around the axon and swelling proximal to the site of entrapment that was attributed to oedema in the study (Brown *et al.* 1976).

It is uncertain as to how much of a role ischaemia plays in nerve entrapment but Fowler *et al.* (1972) have shown that the blood vessels to the nerves are blocked in a mild entrapment neuropathy. It is also known that prolonged ischaemia will result in nerve infarction (Hess *et al.* 1979). Based upon this evidence it is therefore possible that ischaemia may be involved in axonal damage. More recently, Kiernan *et al.* 1999 recorded the sensory and motor action potentials from a number of subjects with a median nerve entrapment at the wrist and also from a number of healthy subjects. Recordings were obtained during a 90 degrees wrist extension that was maintained by the subject for a few minutes. It was found that all subjects developed a conduction block distal to the wrist, with the size of the sensory action potentials being reduced by 50%. All subjects complained of paraesthesia during the wrist extension. The authors suggested that ischaemic compression rather than demyelination of the median nerve at the wrist might explain the intermittent sensory disturbances described by patients with such entrapments (Kiernan *et al.* 1999). Therefore it is possible that changes in the blood flow may be involved in a number of pathophysiological and clinical changes that occur as a result of the entrapment.

## Evidence for central nervous system reorganisation

In view of the field of the present study this section of the introduction is focussed upon evidence for reorganisation within the somatosensory and motor pathways.

Over the past three decades it has become apparent that the central nervous system (CNS) in the adult is not fixed in its connections and function as originally thought. Instead the CNS is capable of being dynamically shaped and altered by many different factors. For example in some genetic strains of mice in which the vibrissae develop abnormally it is found that the pattern of the barrel cell organisation within S1 is modified when compared to mice without the genetic abnormality (Kuljis, 1992).

Experience or training can produce changes in the organisation of the connections within the CNS. By way of illustration, Jenkins *et al.* (1990) conditioned adult owl monkeys to stop a rotating drum with one or more fingers to receive a reward. Conditioned training was carried out over a period of several weeks. It was found that the size of the receptive fields (RF's) mapped after the training were significantly larger than the RF's mapped prior to the conditioned training (Jenkins *et al.* 1990). Similar findings have been reported in a number of other studies (Recanzone *et al.* 1992; Xerri *et al.* 1998).

There is similar evidence from studies in man to suggest that S1 is able to reorganise in movements that require a large amount of learned dexterity. Recording the SEP from a number of subjects have shown that the size of N20 and P22 SEP components of the finger used to read braille elicited following electrical stimulation of the digital nerves of the finger is significantly larger when compared to the non-reading finger. From these findings the authors suggested that reorganisation occurred as a result of learning to read braille (Pascual-Leone & Torres, 1993). In addition studies employing magnetic source imaging have shown that the S1 cortical representation of the fingers of the left hand of string players is larger when compared to a group of control subjects (Pantev *et al.* 1995).

Modification of the peripheral input can produce reorganisation within the CNS. Prolonged periods of electrical stimulation applied to the median nerve of a cat create abnormally large receptive fields within the cortical regions devoted to the median nerve that last for several hours post stimulation (Recanzone *et al.* 1990). More recently, in man it has been demonstrated that prolonged periods of electrical stimulation applied to the pharynx can produce changes in the excitability and organisation of the regions of the motor cortex involved in swallowing (Hamdy *et al.* 1998). More recently Ridding *et al.* (2001) used magnetic stimulation to elicit the MEP from the small hand muscles following a 2 hours of continuous electrical stimulation of the ulnar and radial nerves at the wrist. It was found that the location of the muscle activation shifted significantly and the excitability of the corticospinal projection increased, which the authors suggested reflected reorganisation of the M1 cortex (Ridding *et al.* 2001).

Pre- or post-natal brain damage can also lead to widespread reorganisation within the cortex in man (Lewine *et al. 1994;* Maegaki *et al.* 1995). Recent experiments performed upon adult rats with an induced focal lesion in S1 have shown that the remaining undamaged regions of the cortex surrounding the infarct in S1 reorganise (Coq & Xerri, 1999). Similar changes have been demonstrated following a focal infarct in area 3b of S1 in monkeys (Jenkins & Merzenich, 1987; Xerri *et al.* 1998).

Any loss of the peripheral input such as finger/limb amputation or peripheral nerve injury will produce reorganisation within the CNS. In mice for example, removal of the some or all of the vibrissal follicles results in the reorganisation of the barrel cells in the S1 cortex not evident when compared to healthy control mice (Pidoux *et al.* 1980; Melzer *et al.* 1993).

Following amputation of the middle finger of a monkey, the S1 cortex that has lost the afferent input generated from the amputated finger immediately becomes silent. At the same time there is an associated expansion of the receptive fields of the surrounding unaffected regions of the hand. After several weeks cortex originally exclusive to the input from the amputated digit is taken over by new inputs that have expanded from the surviving regions of the hand (Merzenich *et al.* 1984).

Pons *et al.* (1991) used monkeys to demonstrate that long-term deafferentation involving large areas of the upper limb resulted in an extensive amount of reorganisation within the sensory cortex. It was found that cortex related to facial representation had expanded into the cortical areas previously devoted to the deafferentated upper limb to form a new facial area in addition to the normal facial map. The new facial representation was found to be responsive to stimulation of the face (Pons *et al.* 1991). Related to these findings are parallel experiments upon human subjects that have had the upper limb amputated as a result of injury. Following amputation a proportion of these subjects experience sensations that they believe originate from the amputated region. These are commonly known as 'phantom limb' sensations (Ramachandran, 1993). A number of these patients have reported that when the skin of the face is gently brushed it elicits a phantom sensation localised to a region of the amputated upper limb, with specific areas of the face dedicated to each phantom digit, palm etc. In some subjects there was a second cluster of phantom sensations that were referred to the skin just above the amputated stump, again specific regions of skin denote each phantom finger, palm etc. It was speculated that the phantom sensations reflect reorganisation within S1 following amputation (Ramachandran, 1993). Using magnetic stimulation it was found that stimulation could evoke phantom sensations of movement in the amputated hand or fingers. It also appeared that the motor evoked potentials (MEP's) from muscles ipsilateral to the stump were larger and more easily evoked that the MEP's evoked from the same muscles contralateral to the stump. The authors suggested that these findings could be explained by spinal or cortical reorganisation in the muscles proximal to the amputation stump (Cohen *et al.* 1991).

Evidence obtained from animal and human research suggests that the somatosensory cortex undergoes reorganisation following an injury to a peripheral nerve (Kaas, 1983; Garraghty & Kaas, 1991*a*; Merzenich & Jenkins, 1993). Merzenich & Kaas (1982) used monkeys to demonstrate that a peripheral partial or complete section of the median nerve, triggered the adjacent undamaged cortical neurones (exclusive to the ulnar and radial nerve) to 'expand' into the regions previously responsive to the median nerve within the primary somatosensory cortex. Initially the expanded regions are silent but gradually after a period of approximately 1month, the expanded cortical neurones become responsive to the areas of skin previously exclusive to median nerve innervation territories. Other authors have reported similar findings (Wall *et al.* 1986; Calford & Tweedale, 1990; Garraghty & Kaas, 1991*a*).

There is a sparse amount of evidence to suggest that the CNS reorganises in response to the median nerve entrapment that occurs in CTS in man. A study by Halligan *et al.* (1993) provided the first clue that chronic median nerve entrapment resulting in CTS may reorganise the cortical representations in S1. The study described a subject with phantom limb sensations evoked by tactile stimulation of the face as previously described (Ramachandran, 1993) but whose resultant facial map was modified by pathology prior to amputation. The pathology was carpal tunnel syndrome. Later research by Tinazzi et al. (1998) demonstrated that the N20/P25 cortical components of the somatosensory evoked potential following stimulation of the ulnar nerve are larger in subjects with CTS when compared to a group of normal subjects. The authors presumed that this was due to unmasking and changes in the amount of synaptic strength as a result of the CTS.

The majority of the evidence presented in the previous paragraphs has concentrated on experimental evidence for reorganisation within predominantly S1. There is however evidence that following peripheral nerve injury there is widespread reorganisation throughout many different levels of the CNS.

There is evidence to suggest that the spinal cord reorganises following a peripheral nerve injury. Devor & Wall (1981) reported the changes within the spinal cord that occurred in the adult cat following transection of the sciatic and saphenous nerves. Cutting the nerves deprives the cells in the dorsal horn that respond to the RF's relayed by these nerves. But after 1 – 4 weeks up to 40% of these cells gain a new RF that correspond to the areas of skin that are still innervated. The authors suggested that because there was no evidence of nerve fibre spouting the observed changes were most likely were due to unmasking of previously silent connections (Devor & Wall, 1981). Similar findings have been reported in a number of studies (Whelan & Pearson, 1997; Pearson, 2000).

Evidence for reorganisation in the dorsal column nuclei (DCN) has been demonstrated in a study by Pettit & Schwark (1993). It was found that the RF for a number of identified cells in the DCN reorganised when the afferent supply was removed by administering an anaesthetic (Pettit & Schwark, 1993).

Similarly when the afferent input to the thalamus in the monkey is modified or removed it is associated with a reorganisation of the RF recorded from the ventroposterior lateral nucleus (VPL). The magnitude of the change was reported to be comparable to that observed in the cortex (Garraghty & Kaas, 1991*b*).

As already briefly discussed the motor cortex is also reorganised following removal or modification of the afferent input. Rossini *et al.* (1996) performed experiments on a number of healthy adults. Using magnetic stimulation, MEP's were elicited from the individual prior to and during an anaesthetic block of the median and radial nerves at the wrist. It was found that during anaesthesia the MEP evoked from 1DI shrunk considerably (Rossini *et al.* 1996).

Evidence from a number of studies suggests that unmasking of existent connections is one of the mechanisms by which reorganisation occurs following deafferentation and provides an explanation as to how the CNS is able to reorganise so rapidly (Wall *et al.* 1986; Sanes & Donoghue, 1997). One way that unmasking may occur, is by the removal of local inhibitory circuits (Jacobs & Dongohue, 1991). Another way is by changing the synaptic efficacy. For instance, long-term potentiation/depression is one mechanism by which the CNS can increase or decrease the strength of the synapse connection by down/up regulating local inhibitory connections using NMDA receptors (Hess *et al.* 1996). More recently, Ziemann *et al.* (1998) using magnetic stimulation demonstrated in healthy human subjects that during an ischaemic nerve block the size of the MEP is increased and intracortical inhibition is decreased. Administering a number of different CNS active drugs during the nerve block, they found that this effect is abolished if the subject is given a dose of benzodiazepine (lorazepam) or the $Na^+$ and $Ca^+$ channel blocker (lamotrigine). When a NMDA blocker (dextromethorphan) is given only the decrease in intracortical inhibition is prevented. Based upon these observations, the authors suggested that the changes in MEP size and intracortical inhibition were produced by a decrease of GABA related inhibitory circuits, and appeared to involve $Na^+$ and $Ca^+$ channels (Ziemann *et al.* 1998).

Axonal sprouting is another way that the CNS may reorganise following deafferentation. Evidence for this began in the early seventies when Wall & Egger, 1971 demonstrated that the neocortex of the rat formed new connections after a partial deafferentation (Wall & Egger, 1971). Similarly Jones & Schallert (1992) showed that following an induced unilateral lesion of the motor cortex of the rat there is an increase in the dendritic arborization of layer V of the pyamidal neurones over a number of months, peaking at 2-4months (Jones & Schallert, 1992).

The following sections present evidence to suggest that reflex reorganisation within the CNS occurs following a peripheral nerve injury produced by entrapment of the median nerve in carpal tunnel syndrome.

## Summary

1. Reflex cutaneomuscular responsiveness to stimulation of the digital nerves of the little finger has been investigated in subjects with carpal tunnel syndrome, a chronic partial median nerve entrapment at the wrist (CPNE) and compared to a group of healthy control subjects.

2. Recordings were obtained from the preferred hand of 17 adult subjects with CPNE and 12 healthy subjects. CPNE subjects were diagnosed using nerve conduction studies prior to reflex recording.

3. With ethical approval and informed consent, surface EMG was recorded from first dorsal interosseous (1DI) muscle and the sensory nerve action potential (SNAP) recorded from the ulnar nerve whilst electrically stimulating the digital nerves of the little finger (2.5 X sensory threshold, 100μS, 5Hz). Subjects performed a sustained weak abduction of the index finger against resistance at 10/20% MVC.

4. The E2 reflex component recorded from 1DI following stimulation of the digital nerves of the little finger was present in 62% of CPNE compared to 13% of control subjects. The mean size of the E2 component recorded from the CPNE and control subjects was significantly different (Mann-Whitney test, $P = 0.0001$).

5. The presence of the E2 reflex component was associated with the mild (Chi-square test, $P = 0.014$) but not moderate or moderate/severe (Chi-square test, $P = 0.104$) median nerve entrapment.

6. The mean size of the E1 & I1 components recorded from the CPNE and control subjects were not significantly different (Mann-Whitney test, E1, *P* = 0.089; I1, *P* = 0.934).

7. In addition to the usual reflex components, a very long latency decrease in EMG, late I, was recorded from 1DI following little finger digital nerve stimulation in 19% of the trials recorded from the carpal tunnel subjects and 18.5% of the trials recorded from the healthy controls. A later increase in EMG, late E, was recorded in 42% of the trials recorded from the carpal tunnel subjects compared to 12.9% of the trials recorded from the healthy controls.

8. It was found the mean size of the late I recorded from the subjects with carpal tunnel syndrome was not significantly different to the mean size of the late I seen in the recordings obtained from the healthy control subjects (Mann-Whitney test, *P* = 0.753). In contrast the mean size of the late E was significantly larger in the carpal tunnel compared to the healthy control subjects (Mann-Whitney test, *P* = 0.002).

9. The presence of the late E was independent of the severity of the median nerve entrapment (Chi-square test, Mild CPNE, *P* = 0.100; Moderate & Moderate/severe CPNE, *P* = 0.142).

10. There was no significant difference in SNAP size recorded from the ulnar nerve in healthy and CPNE subjects (t-test, *P* = 0.081).

11. The mean size of the reflex components E1, I1 and E2 elicited from 1DI following index finger stimulation were significantly reduced in the subjects with carpal tunnel syndrome

compared to the control subjects (Mann-Whitney test, E1, $P = 0.001$; I1, $P = 0.0001$; E2, $P = 0.0001$).

12. The mean size of the very long latency components Late I and late E elicited from 1DI following index finger stimulation in the subjects with carpal tunnel syndrome were not significantly different when compared to the control subjects (Mann-Whitney test, Late I, $P = 0.962$; Late E, $P = 0.144$).

13. It is concluded that the E2 component associated with distant digital nerve stimulation of the little finger seen in subjects with CPNE reflects reorganisation within the CNS, resulting from interruption of afferent input to the primary sensory cortex following median nerve entrapment.

## Introduction

In carpal tunnel syndrome (CTS), the afferent supply provided by the median nerve is disrupted or lost whilst the efferent supply provided by the ulnar nerve to the muscle 1DI remains intact. Given this naturally occurring model, the purpose of this study is to investigate whether reflex cutaneomuscular responsiveness to stimulation of the digital nerves of the little finger is reorganised in the hand, resulting from the interruption of the afferent input to the sensory cortex following median nerve entrapment.

If the cortical area within the primary somatosensory cortex responsive to the afferent inputs from territory of ulnar nerve do indeed expand to encompass areas of the cortex previously devoted to the cutaneous afferent inputs from the median nerve as has been shown in earlier work (Merzenich & Kaas, 1982). It could be hypothesised that stimulation of the skin of the fifth finger in subjects with such a peripheral nerve entrapment may produce reflex effects from 1DI not seen in healthy control subjects.

### Aims

- To record the cutaneomuscular reflex (CMR) from a number of healthy volunteer control subjects without evidence of CTS, to compare with the CMR recordings obtained from a group of CTS patients.

- To look for evidence of reflex reorganisation, in CTS patients.

## Methods

The study was carried out with local ethical committee approval and the protocols were carried out in accordance to the declaration of Helsinki, 1964. Informed consent was obtained from all subjects. The study is of an unmatched case-control design. It is intended to compare the cutaneomuscular reflex recorded from 1DI following stimulation of the distant little finger in a group of control subjects, with that obtained from a group of individuals with carpal tunnel syndrome, a chronic median nerve entrapment.

### *Subjects*

The subjects for the control and for the CTS groups were selected in accordance with the inclusion/exclusion guidelines (see appendix A).

### *Control subjects*

Experiments were performed on the preferred hand of 12 subjects (aged 19-58 years, 10 female). All subjects were healthy and free from neurological disease or peripheral nerve pathology.

### *Carpal tunnel syndrome subjects*

Recordings were obtained from 17 subjects (aged 43-78years, 15 female) with electrodiagnostic changes in the sensory nerve action potential and/or motor nerve conduction compatible with the diagnosis of CTS. The resident Consultant Neurophysiologist (who was blind to the results) graded the severity of entrapment. Appendix B shows the criteria used to grade the severity of entrapment. In addition each subject was asked a number of questions regarding the clinical symptoms experienced. The question sheet is shown in appendix C.

### *Other subjects*

In addition recordings were obtained from one individual (aged 40years, female) with a right median nerve transection and one individual (aged 23, female) with a left index finger amputation just above the proximal phalangeal joint.

### *Cutaneous reflexes*

Reflexes were recorded from 1DI. The ongoing muscle activity was recorded in the same manner as described in section 1.

### *Sensory Volleys*

Sensory volleys were recorded from the nerve over the wrist using self-adhesive surface electrodes as described in section 1.

### *Stimulation of the digital nerves*

The digital nerves of (a) the index or (b) the little finger were stimulated via ring electrodes placed either side of the proximal interphalangeal joint as described in section 1.

### *Experimental procedure for control and case subjects*

Recordings were obtained from 1DI whilst stimulating the digital nerves of (a) the index finger and (b) the little finger. The subject was instructed to perform either a sustained abduction of the index finger. To maintain a constant contraction between 10-20% of the maximum, a visual aid was provided for the subject. Reflex modulations of the EMG produced in 1DI and sensory nerve volleys for each movement task were recorded on 2 occasions following index finger stimulation (to establish the presence of reflex) and on 2 occasions following little finger stimulation where ever possible in the same recording session.

## *Analysis*

### *Cutaneous reflexes*

The mean area percent modulation of each component was measured and calculated for each component for each 250 average as described in section 1.

### *Sensory volleys*

The size of the SNAP was measured as described in section 1.

## *Statistical analysis*

The normality of the data was established as per section 1. The significance of each task upon the components of the reflex was examined by performing a t-test, Chi-square or Mann-Whitney test where appropriate. The level of significance was set at $P < 0.05$.

### *Type I errors & the Bonferroni adjustment*

The statistical tests employed in the preceding paragraph assume that each observation within a group of observations is sampled independently of each other. Failure to observe this assumption can bias the sample group, resulting in an increased risk of a type I error (false positive) occurring. Employing the Bonferroni adjustment reduces this risk

(Samuels & Witmer, 1999*b*). A detailed description of the procedure is provided on pages 94 & 95.

In this part of the present thesis, the exact *P* values calculated using t-tests, Chi-square and the Mann-Whitney test have been given. Therefore any reader of the present thesis can perform the Bonferroni adjustment if it is felt that the observations sampled are not sufficiently independent of each other.

## Results

### *A. Healthy control subjects*

In the preceding chapter of this thesis cutaneomuscular reflex responses were recorded from 1DI during a sustained abduction of the index finger following stimulation of the digital nerves of the distant little finger in a number of healthy individuals (selected according to the exclusion/inclusion criteria described in appendix A). As previously discussed, the reflex responses recorded during these experiments were performed to establish a set of control values for each reflex component (part, A, section, 3). In summary, the findings during index finger abduction were as follows:

### *Reflexes obtained from 1DI following stimulation of the digital nerves of the little finger*

Data taken from results table 1*A* (page 137) and table 3 (page 142)

- The E1 component was present in 48%, the I1 was present in 22% and the E2 component was present in only 13% of all trials.

- On combining the % modulation data obtained from all trials for each reflex component (*n* = 54), the mean ± 1 S.E.M size of the E1 component measured 4.38 ± 0.67, the I1 component measured 1.85 ± 0.52 and the E2 component measured 0.75 ± 0.28.

- The sensory nerve volley recorded from the ulnar nerve was present in 100% of trials and the mean ± 1S.E.M measured 7.05 ± 0.62µV.

- In addition to the reflex components, E1, I1 & E2, a very long latency decrease in the EMG, late I was recorded in 18.5% of the trials. The mean size ± 1 S.E.M (% modulation) measured 2.0 ± 0.20. A later excitatory increase in the EMG, late E was present in 12.9% of the recordings. The mean size ± 1 S.E.M (% modulation) measured 1.02 ± 0.10.

*Reflexes obtained from 1DI following stimulation of the digital nerves of the index finger*

Data taken from results figure 22*A* (page 135) and table 3 (page 142)

- The E1 component was present in 85%, the I1 was present in 100% and the E2 component was present in 100% of all trials.

- On combining the % modulation data obtained from all trials for each reflex component (*n* = 22), the mean ± 1 S.E.M size for the E1 component measured 9.11 ± 1.3, the I1 component measured 12.39 ± 1.6 and the E2 component measured 17.48 ± 1.6.

- The sensory nerve volley recorded from the ulnar nerve was present in 100% of trials and the mean ± 1 S.E.M measured 13.1 ± 0.93µV.

- A very long latency decrease in EMG, late I was recorded in 9.1% of the trials. The mean size ± 1 S.E.M (% modulation) measured 0.96 ± 0.08. The late excitatory increase in the EMG, late E was present in 4.5% of the recordings. The mean size ± 1 S.E.M (% modulation) measured 0.2 ± 0.01.

### *B. Carpal tunnel syndrome subjects*

This group comprised of 17 subjects, all had clinical symptoms consistent with carpal tunnel syndrome (selected according to the exclusion/inclusion criteria in appendix A). In each subject the diagnosis of carpal tunnel syndrome was confirmed by performing sensory and motor nerve conduction upon the hand prior to participation.

### *Grading of carpal tunnel syndrome*

The severity of median nerve entrapment within the carpal tunnel was determined by the set of criteria shown in appendix B. In the present study 56% were graded as having a mild entrapment, 6% were graded as moderate entrapment and 29% were graded as moderate/severe median nerve entrapment.

### *Clinical presentation and symptoms*

Table 4 and 5 show the data collected from the questionnaire completed by each subject.

#### *Age*

The mean ± 1 S.E.M age of all subjects was 58.5 ± 14.2 years. When the subjects were divided into those with a moderate/severe entrapment the mean ± 1 S.E.M age of the subjects was found to be 65.2 ± 18.7 years ($n = 5$). The mean ± 1 S.E.M age was found to be 55.7 ± 13.5 years ($n = 12$) in the subjects with a mild/moderate entrapment. Although the mean age was greater in the subjects with a moderate/severe compared to the mild entrapment, this difference was not significant when compared using a t-test ($P = 0.073$).

*Gender*

Of the subjects studied in the present study 88% were female and 22% were male. The ratio of females to males was found to be 4: 1.

*Duration*

The mean duration ± 1 S.E.M of clinical symptoms was 1.2 ± 0.29 years and the mode was 0.5 years when the data for all subjects is combined. When the duration of symptoms obtained from all subjects is separated according to the grade of severity of entrapment, it was found that in subjects with a moderate/severe entrapment, the mean duration ± 1 S.E.M of clinical symptoms was 2.8 years ($n$ = 5) and the mode was 2 years. In the subjects with a mild or moderate entrapment, the mean duration ± 1 S.E.M of clinical symptoms was 0.6 ± 0.14 years ($n$ = 12) and the mode was 0.5 years. An unpaired t-test comparing the mean duration in the subjects with a moderate/severe entrapment was significantly longer than subjects with a mild entrapment ($P$ = 0.0194).

*Sensory disturbances*

Of all subjects 88% suffered from intermittent pins and needles whilst in the remaining 12% pins and needles were persistent.

Intermittent or persistent numbness was reported in 47% and 12% of subjects whilst the remaining 41% did not suffer any numbness.

Pain, which was intermittent, was reported by 88% of subjects. 12% of subjects experienced no pain. Persistent pain was not reported by any of the subjects. The mean pain rating when the scores for all of the subjects in the group were combined was 3.0. When the subjects were divided into those with a moderate/severe and mild/moderate entrapment, the mean ± 1 S.E.M pain rating score in subjects with a moderate/severe entrapment was 4.8 ±

0.97, compared to 2.7 ± 0.65 in subjects with a mild entrapment. The mean pain rating score for the moderate/severe subjects ($n = 5$) was significantly higher when compared to the mean pain rating score reported by the mild entrapment subjects ($n = 12$) (t-test, $P = 0.0211$).

### *Occurrence of sensory disturbances*

Sensory disturbances were reported by 94% of subjects on waking. Symptoms were less frequent during the day with 71% of subjects reporting no symptoms. 71% of subjects reported symptoms during the night.

### *Location of symptoms*

Sensory disturbances in the digits and palmar surface of the hands were reported by 100% of subjects. In addition 17.6% of all subjects reported symptoms that extended to the forearm and 5.8% of subjects reported symptoms that extended to the shoulder level.

### *Functional hand deficits*

Of all subjects 36% reported no functional deficit. 32% of subjects reported dropping objects and 16% of subjects reported difficultly in holding objects for any length of time. A decrease in the quality of handwriting was reported by 16% of subjects.

### *Muscle wasting and Tinel's sign*

There was no evidence of wasting of the thenar eminence muscles in 94% of all subjects. Tinel's sign was positive in 65% of subjects.

**Table 4. Summary of the clinical features of carpal tunnel syndrome described by the subjects**

| Subject | Duration yrs | Range of symptoms | | | | Occurence of Sx | | | Location of Sx | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Pins/needles | Numbness | Pain | Pain rating | On waking | during day | at night | in fingers | in other regions |
| 1 | 1 | Y- I | Y- I | Y - I | 6 | Y | N | Y | d1 - d4 | hand |
| 2 | 4 | Y - I | Y - I | Y - I | 4 | Y | Y | Y | d1 - d3 | hand + forearm |
| 3 | 0.5 | Y - P | Y - P | Y - I | 5 | Y | Y | Y | d2 -d3 | |
| 4 | 0.5 | Y - I | Y - I | N | 0 | Y | N | N | d1 - d4 | hand |
| 5 | 2 | Y - I | Y - I | Y - I | 3 | Y | N | Y | d1-d3 | hand |
| 6 | 0.5 | Y - I | Y - I | Y - I | 3 | Y | N | Y | d1 -d4 | hand |
| 7 | 5 | Y - P | Y - P | Y - I | 7 | Y | N | N | d1 - d5 | hand |
| 8 | 0.5 | Y - I | N | Y - I | 3 | Y | N | N | d1-d5 | hand + forearm |
| 9 | 0.5 | Y - I | N | N | 0 | Y | Y | N | d1-d3 | |
| 10 | 0.3 | Y - I | N | Y - I | 2 | Y | N | Y | d1- d4 | hand |
| 11 | 1 | Y - I | Y - I | Y - I | 4 | Y | N | Y | d1 - d4 | hand |
| 12 | 1 | Y - I | N | Y - I | 2 | Y | Y | N | d1 - d3 | |
| 13 | 0.5 | Y - I | N | Y - I | 2 | N | N | Y | d1- d5 | hand |
| 14 | 2 | Y - I | Y - I | Y - I | 4 | Y | N | Y | d1-d5 | hand |
| 15 | 0.5 | Y - I | Y - I | Y - I | 4 | Y | Y | Y | d1-d5 | hand forearm shoulder |
| 16 | 0.5 | Y - I | N | Y - I | 3 | Y | N | Y | d2 - d3 | |
| 17 | 0.5 | Y - I | N | Y - I | 4 | Y | N | Y | d1- d3 | |

**Table 5. Summary of the clinical features of carpal tunnel syndrome described by the subjects (continued).**

| Subject | Gender | Age | Grade of CTS | Side investigated | Threshold mA<br>Median<br>Index finger | Threshold mA<br>Ulnar<br>Little finger | Muscle wasting | Tinels sign | Functional deficits |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 1 | 58 | MOD/SEV | R | 5 | 3 | N | - | Dropping objects, poor handwriting |
| 2 | 1 | 78 | MOD/SEV | R + L |  | 6 | Y | + | Decrease in fine hand function |
| 3 | 1 | 72 | MOD | R | 6.5 | 4 | N | + | holding objects |
| 4 | 1 | 43 | MILD | L | 5 | 4 | N | - | None |
| 5 | 1 | 55 | MOD/SEV | R | 7 | 4 | N | + | None |
| 6 | 2 | 57 | MILD | R | 5 | 4 | N | + | Less control with pen affects handwriting |
| 7 | 1 | 58 | MOD/SEV | R | 10 | 4 | N | + | Dropping things |
| 8 | 1 | 52 | MILD | R | 4.5 | 4 | N | - | None |
| 9 | 2 | 43 | MILD | R | 4 | 4 | N | - | None |
| 10 | 1 | 50 | MILD | R | 6 | 4.5 | N | + | Numbness during driving |
| 11 | 1 | 77 | MOD/SEV | R | 7.5 | 4 | N | - | Handwriting, holding objects |
| 12 | 1 | 69 | MILD | R | 5.5 | 1.5 | N | + | None |
| 13 | 1 | 53 | MILD | R | 3.5 | 3 | N | + | Dropping objects, holding objects |
| 14 | 1 | 54 | MILD | R | 4.5 | 4 | N | + | None |
| 15 | 1 | 68 | MILD | R | 6.9 | 3 | N | + | Knitting |
| 16 | 1 | 61 | MILD | R | 4 | 4.4 | N | + | None |
| 17 | 1 | 46 | MILD | R | 3.9 | 3.5 | N | - | Dropping things |

### *Thresholds*

The sensory thresholds for the median and ulnar nerves were measured in each subject. The mean ± 1 S.E.M median nerve threshold when the data from all subjects was combined measured 5.55 ± 1.34mA (*n* = 16 (median SNAP not recorded in one subject)) and the ulnar nerve threshold measured 3.81 ± 0.92mA (*n* = 17). The mean median nerve threshold was significantly higher than the mean ulnar nerve threshold obtained from all subjects (t-test, *P* = 0.0001).

The data from all subjects was divided into moderate/severe and mild/moderate entrapment. The mean ± 1 S.E.M median nerve threshold in subjects with a moderate/severe entrapment measured 7.35 ± 1.81 (*n* = 4) and the mean median nerve threshold in subjects with a mild/moderate entrapment measured 4.94 ± 1.2 (*n* = 12). The mean median nerve threshold was found to be significantly greater in subjects with a moderate/severe entrapment when compared to subjects with a mild entrapment (t-test, *P* = 0.0432).

The mean ulnar nerve thresholds for subjects with a moderate/severe entrapment measured 3.65 ± 0.88 (*n* = 5) and 4.20 ± 0.97 (*n* = 5) in subjects with a mild entrapment. There were no significant differences when compared using an unpaired t-test (*P* = 0.179).

### *Reflexes obtained from 1DI following stimulation of the digital nerves of the little finger in subjects with carpal tunnel syndrome*

The cutaneomuscular reflex recorded from 1DI during a sustained index finger abduction following stimulation of the digital nerves of the little finger in a healthy individual are shown in Fig. 28*A*. Stimulation elicits an initial increase in EMG, E1, followed by a decrease, I1. An E2 component is not elicited. The % EMG modulation measured 11.6 and 5.7 respectively.

Figure 28*B-G* show the pattern of reflex responses recorded from 1DI following stimulation of the little finger digital nerves recorded from a number of individuals with carpal tunnel syndrome. Stimulation failed to elicit any reflex effects upon the EMG recorded from 1DI in this individual. This is illustrated in fig. 28*B*.

In contrast, figure 28*C* shows the effect of stimulating the digital nerves of the fifth finger in another individual. In this case, stimulation elicits a series of modulations in the EMG recorded from 1DI. There is an initial increase, E1, followed by a decrease, I1, followed by an increase, E2, followed by a second decrease, late I, followed by a third increase, late E, in the EMG. The % EMG modulations in this individual measured 15.2,29.3,4.1,2.2 & 16.2 respectively.

Figure 28*D* shows the reflex modulations recorded from 1DI in another individual. In this example stimulation of the digital nerves of the little finger elicits fails to elicit any components other than a very long latency increase in EMG, Late E. The % EMG modulation measured 3.1.

A further pattern of reflex modulations in the EMG recorded from 1DI following little finger digital nerve stimulation is elicited in this individual producing and increase in EMG, E2, followed by a second increase in EMG, late E. The % EMG modulations measured 4.8 & 15.3% respectively. This is shown in figure 28*E*.

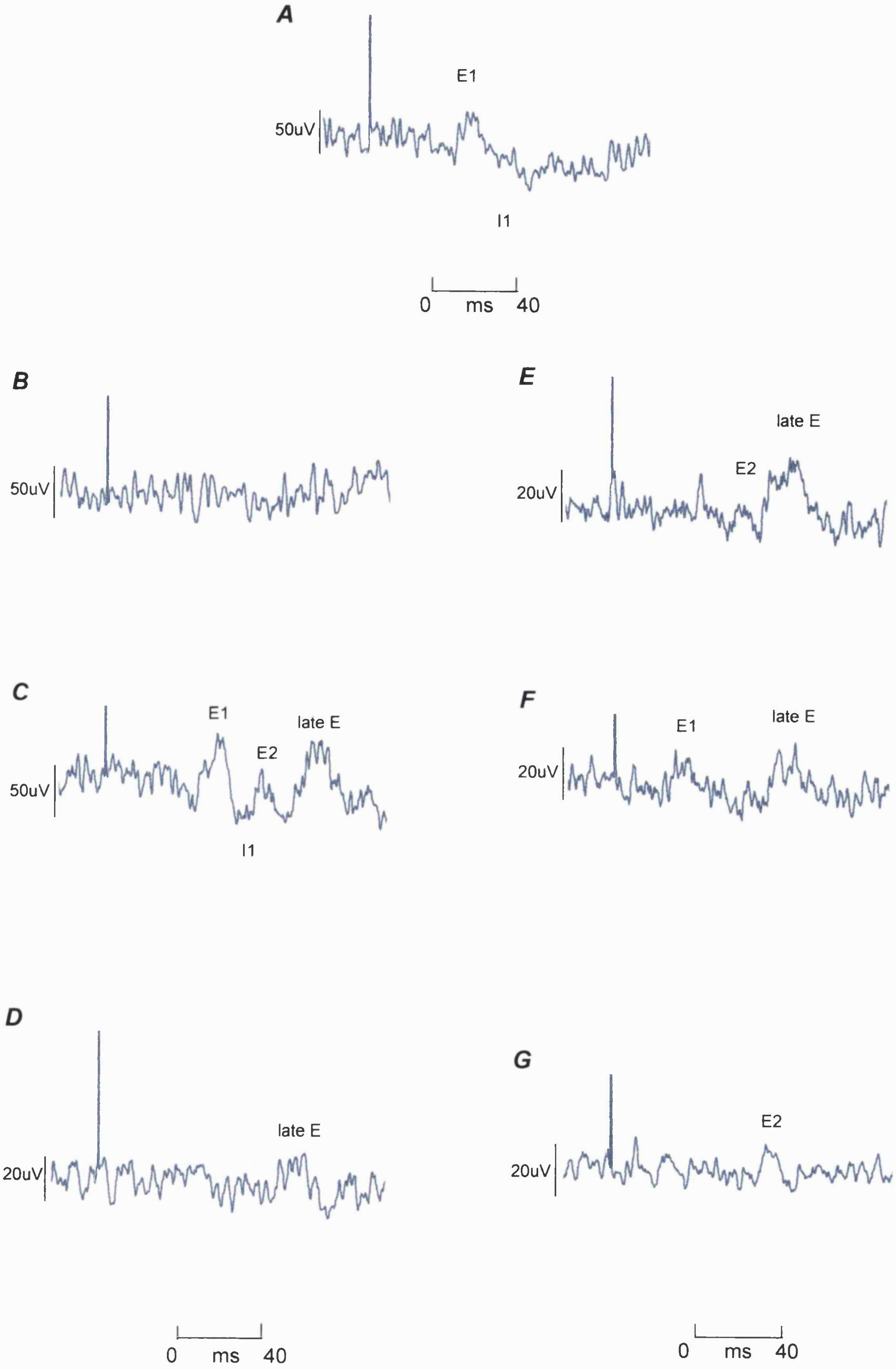

A
E1
50uV
I1
0 ms 40
B
50uV
E
late E
E2
20uV
C
E1
late E
E2
50uV
I1
F
E1
late E
20uV
D
late E
20uV
G
E2
20uV
0 ms 40
0 ms 40

**Figure 28. Cutaneous reflex response recorded from 1DI following digital nerve stimulation of the little finger in a healthy individual and several individuals with carpal tunnel syndrome**

*A-G,* Cutaneous reflex response recorded from 1DI following stimulation of the digital nerves of the little finger during a light sustained voluntary contraction of 1DI produced by performing abduction of the index finger at 10-20% MVC. *A,* Healthy individual. A reflex response is evoked consisting of an increase in EMG, E1, followed by a decrease, I1. *B-G,* Carpal tunnel subjects. *B,* no reflex modulations are seen in 1DI in this individual. *C,* reflex response elicited, consists of a series of increases and decreases in the EMG, E1, I1, E2, late I & late E. *D,* cutaneous reflex recorded in this subject consists of a late E. *E,* reflex response elicited consists of a long latency increase in EMG, E2 followed by second increase, late E. *F,* reflex response elicited consists of an early increase in EMG, E1 followed by a very long latency component, late E. *G,* reflex response elicited consists of a long latency increase in EMG, E2. *A-G,* shows the averaged rectified EMG time locked to each stimulus, presented at 5s$^{-1}$. 250 sweeps. Recorded in different sessions.

Figure 28*F* shows another pattern of reflex modulation in the EMG recorded from 1DI following stimulation of the little finger digital nerves. In this example stimulation elicits an early increase in EMG, E1 followed by a very long latency increase in EMG, late E. The % EMG modulations measured 4.6 and 4.8 respectively.

In the last example, stimulation of the digital nerves of the little finger elicited a late increase in the EMG recorded from 1DI, E2. No other reflex modulations were evident. This is shown in Fig. 28*G*. The % EMG modulation measured was 4.8.

On combining the data obtained from all subjects (shown in table 6) it was found that, in 2 of the 17 subjects, stimulation of the little finger digital nerves failed to elicit any reflex modulation of the EMG recorded from 1DI. Both subjects were graded as having a mild entrapment.

In 4 subjects, a series of reflex modulations were seen in the EMG recorded from 1DI consisting of E1, I1, E2, late I and late E. Moderate or moderate/severe entrapment was diagnosed in 3 out of the 4 subjects.

The E2 and late E components of the reflex response elicited following stimulation of the digital nerves of the little finger was seen in 3 subjects. All were diagnosed as having a mild entrapment.

In a single individual, stimulation elicited the E1 and late E components of the reflex response. This individual was diagnosed as having a moderate/severe entrapment.

In the remaining 6 subjects, only the E2 component of the reflex response was present following stimulation of the little finger digital nerves. All were diagnosed as having a mild entrapment.

| | Reflex components present | | | | | |
|---|---|---|---|---|---|---|
| | No change | E2 only | E2 & late E | E1 & late E | E1, I1, E2, late I & late E | Late E only |
| Total number of subjects | 2 | 6 | 3 | 1 | 4 | 1 |
| Number of subjects with Mild CTS | 2 | 5 | 3 | 0 | 1 | 0 |
| Number of subjects with moderate or moderate/severe CTS | 0 | 1 | 0 | 1 | 3 | 1 |

**Table 6. Summary of the components of the reflex response recorded from 1DI following little finger digital nerve stimulation obtained from all subjects with carpal tunnel syndrome and with the grade of entrapment**

From the combined data obtained from all subjects it was found that the presence of the E2 component was associated with mild (Chi-square test, $n$ = 17, $P$ = 0.014) but not moderate or moderate/severe (Chi-square test, $n$ = 17, $P$ = 0.104) carpal tunnel entrapment. The presence of the late E component was not associated with the severity of the carpal tunnel entrapment (Chi-square test, $n$ = 17, $P$ = 0.100 for both mild and $P$ = 0.142 for moderate or moderate/severe entrapment).

The mean size for each reflex component recorded from 1DI following little finger digital nerve stimulation in all subjects is shown in table 7.

Taking the data as a whole, the E1 component, with a mean onset latency of 33.2ms was recorded from 1DI on 19.2% of trials. The I1 component, with a mean onset latency of 48.6ms was obtained in 23% of trials and the E2 component, with a mean latency onset of 59.3ms was obtained in 61.5% of trials.

In addition to the usual reflex modulations, two very long latency modulations were recorded from 1DI in a number of the subjects. At times a second very long latency decrease in the EMG, late I, with a mean onset latency of 72.9ms was recorded from 1DI. This component was seen in 19.2% of trials. More frequently, a very long latency increase in EMG, late E, with a mean onset latency of 75.9ms was recorded from 1DI. This was seen in 41% of the trials.

| | **Reflex component**<br>% modulation | | | | |
|---|---|---|---|---|---|
| *N* = *26* | E1 | I1 | E2 | Late I | Late E |
| Mean | 2.50 | 2.42 | 5.96 | 1.76 | 4.43 |
| Standard deviation | 5.55 | 6.51 | 6.48 | 4.31 | 6.15 |
| S.E.M | 0.49 | 0.48 | 1.16 | 0.34 | 0.87 |
| % responses present | 19.2 | 23.0 | 61.5 | 19.2 | 42.0 |

**Table 7. Summary of the components of the reflex response recorded from 1DI following little finger digital nerve stimulation obtained from all subjects with carpal tunnel syndrome**

A significant difference was found in the mean ± 1 S.E.M size of the E2 (5.96 ± 1.16) and late E (4.43 ± 0.87) components recorded from the carpal tunnel subjects (*n* = 26) when compared to the mean size of the E2 (0.75 ± 0.28) and late E (1.02 ± 0.10) component obtained from the healthy (*n* = 54) subjects (Mann-Whitney test, E2, *P* = 0.0001; late E, *P* = 0.0020). The mean size of the E1 (2.5 ± 0.49), I1 (2.42 ± 0.48) and late I (1.76 ± 0.34) components obtained from the carpal tunnel subjects were not significantly different when compared to the E1 (4.38 ± 0.67), I1 (1.85± 0.52) and late I (2.00 ± 0.20) components obtained from the healthy controls (Mann-Whitney test, E1, *P* = 0.089; I1, *P* = 0.934; Late I, *P* = 0.753).

The mean ± 1 S.E.M size of the SNAP recorded from over the ulnar nerve at the wrist from all subjects with carpal tunnel syndrome measured 7.9µV ± 1.77. The mean size of the ulnar SNAP was not significantly different when compared to the mean size of the ulnar nerve SNAP recorded from the healthy control subjects (t-test, *n* = 20, *P* = 0.081).

### *Reflexes obtained from 1DI following stimulation of the digital nerves of the index finger in subjects with carpal tunnel syndrome*

Cutaneomuscular reflex recorded from 1DI following stimulation of the digital nerves of the index finger showed 2 distinct patterns. Figure 29*A* shows the reflex recorded from 1DI following stimulation of the index finger digital nerves in a single individual. In this case stimulation elicits a clear triphasic reflex response consisting of a short latency increase, E1, followed by a decrease, I1, followed by a second increase, E2. The % EMG modulations measured were 6.5, 15.2 & 13.9 respectively. In contrast, figure 29*B* shows the effects of stimulating the digital nerves of the index finger upon the EMG recorded from 1DI in another individual. In this case stimulation fails to elicit the usual triphasic reflex response.

When the data from all subjects is added together, the E1 component, with a mean onset latency of 35.4ms was recorded from 1DI on 31.8% of trials. The I1 component, with a mean onset latency of 45.5ms was obtained in 27% of trials and the E2 component, with a mean latency onset of 57.0ms was obtained in 31.8% of trials.

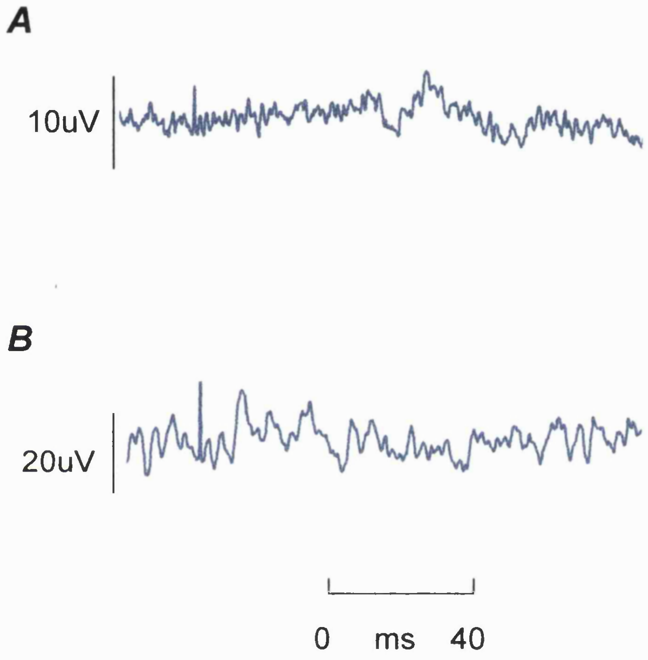


**Figure 29. Cutaneous reflex response recorded from 1DI following digital nerve stimulation of the index finger in two individuals with carpal tunnel syndrome**

*A-B,* Cutaneous reflex response recorded from 1DI following stimulation of the digital nerves of the index finger during a light sustained voluntary contraction of 1DI produced by performing abduction of the index finger at 10-20% MVC. *A,* A reflex response is evoked consisting of an increase in EMG, E1, followed by a decrease, I1, followed by a second increase, E2. *B,* no reflex modulations are seen in 1DI in this individual. *A-B,* shows the averaged rectified EMG time locked to each stimulus, presented at 5s$^{-1}$. 250 sweeps. Recorded in different sessions.

A reflex response was recorded from 1DI following index finger digital nerve stimulation in 7 out of 16 subjects (one subject declined). This group consisted of 6 subjects with a mild and 1 subject with a moderate carpal tunnel entrapment. Of the remaining 9 subjects in which, a reflex response was not recorded from 1DI, 5 subjects were diagnosed as having a mild entrapment whilst the remaining 4 subjects had a moderate/severe entrapment.

The data for all subjects are shown in table 8. The mean ± 1 S.E.M size of the reflex components E1 (2.89 ± 0.61), I1 (3.73 ± 0.79) & E2 (5.14 ± 1.1) elicited from the carpal tunnel syndrome subjects (*n* = 22) following stimulation of the digital nerves of the index finger were found to be significantly smaller than the mean size of the E1 (9.11 ± 1.3), I1 (12.39 ± 1.6) & E2 (17.48 ± 1.6) reflex components recorded from the healthy control subjects (*n = 22)* when compared using a t-test (Mann-Whitney test, E1, *P* = 0.001; I1, *P* = 0.0001; E2, *P* = 0.0001).

| | **Reflex component**<br>% Modulation | | | | |
|---|---|---|---|---|---|
| *N* = 22 | E1 | I1 | E2 | Late I | Late E |
| Mean | 2.89 | 3.73 | 5.14 | 0.64 | 0.97 |
| Standard deviation | 4.95 | 6.47 | 7.46 | 2.45 | 2.47 |
| S.E.M | 0.61 | 0.79 | 1.1 | 0.14 | 0.21 |
| % responses present | 31.8 | 27.0 | 31.8 | 9.10 | 18.0 |

**Table 8. Summary of the components of the reflex response recorded from 1DI, following index finger digital nerve stimulation obtained from all subjects with carpal tunnel syndrome**

There was no significant difference in the mean size ± 1 S.E.M of the late I (0.64 ± 0.14) and late E (0.97 ± 0.21) components recorded from 1DI following stimulation of the digital nerves of the index finger in the subjects with carpal tunnel syndrome when compared to the late I (0.96 ± 0.08) and late E (0.20 ± 0.01) components obtained from the healthy control subjects (Mann-Whitney test, $n$ = 22, late I, $P$ = 0.962; late E, $P$ = 0.144).

### *C. Reflexes recorded from a single subject with a median nerve transection*

#### *Clinical presentation*

As an 11 year old (now 40years) this lady fell through a plate glass window, transecting the right median nerve and flexor tendons of the thumb at the level of the wrist. Ever since she has had no sensation in the right index and middle finger. She has a little sensation in the thumb. The sensation in the ring and little fingers seem to be normal. The left hand appears to be healthy.

Figure 30*A* shows the cutaneomuscular reflex recorded from 1DI following stimulation of the digital nerves of the right index finger (affected side). In this case, stimulation fails to elicit a reflex response from the right 1DI. In contrast when the digital nerves of the right little finger are stimulated, a clear triphasic response is elicited, consisting of an increase in EMG, E1, followed by a decrease, I1, followed by a second increase, E2. The % EMG modulations for each component measured 10.1,3.3 & 15.3 respectively. This is illustrated in Fig. 30*B*.

In comparision when the digital nerves of the index finger on the left (unaffected side) are stimulated, (Fig. 30*C) a* clear reflex response is elcited from the left 1DI, consisting of an increase in EMG, E1, followed by a decrease, I1, followed by an incease, E2. The % EMG modulations measured 19.8, 9.4 & 25.1 respectively. When the stimulus is moved to the digital nerves of the left little finger illustrated in Fig. 30*D*, stimulation fails to elcit any reflex response in the left 1DI muscle.

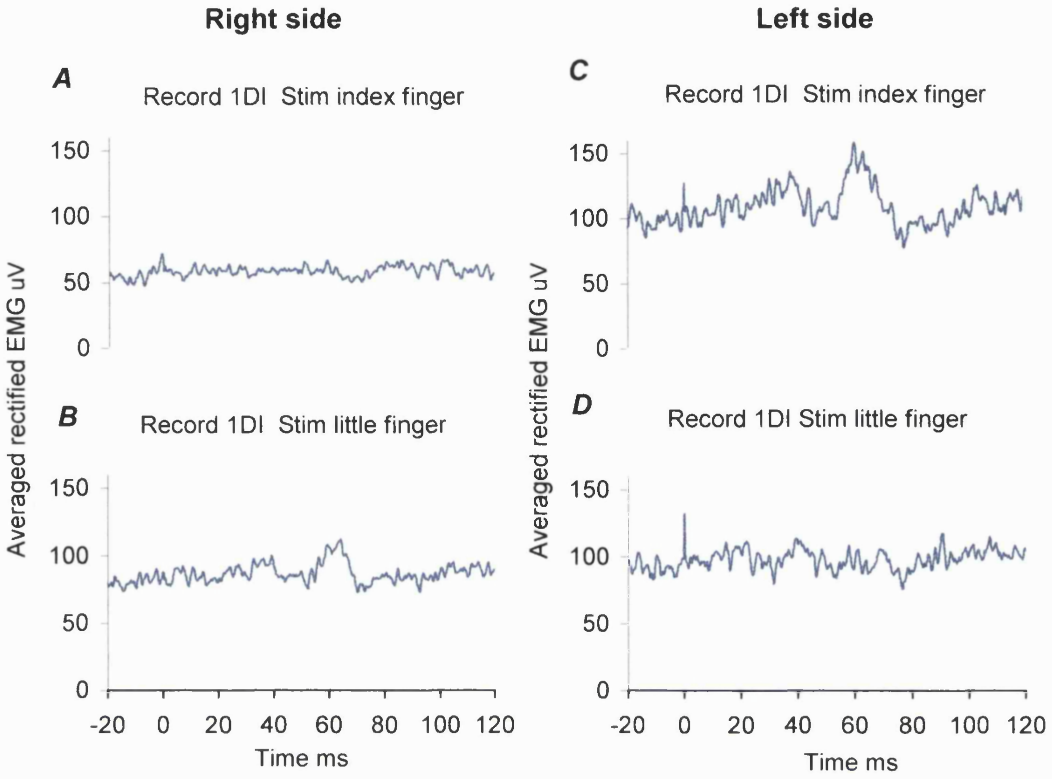


**Figure 30. Cutaneous reflex response recorded from 1DI following digital nerve stimulation of the index finger in an individual with a right median nerve transection at the wrist**

Cutaneomuscular reflex recorded from 1DI following stimulation of the digital nerves of (a) the index and (b) the little finger during a light sustained voluntary contraction of 1DI produced by performing abduction of the index finger at 10-20% MVC. *A,* No reflex response is evoked from the right 1DI following stimulation of the index finger digital nerves (median nerve transected). *B,* Stimulation of the little finger digital nerves evokes a reflex response in the right 1DI consisting of a small increase in EMG, E1, followed by a decrease, I1, followed by a second increase, E2. *C,* A reflex response is evoked from the left 1DI following stimulation of the digital nerves of the index finger, consisting of an increase in EMG, E1, followed by a decrease, I1, followed by a second increase, E2. *D,* no reflex modulations are seen in the left 1DI following stimulation of the little finger digital nerves. *A-D,* show the averaged rectified EMG time locked to each stimulus, presented at $5s^{-1}$. 250 sweeps. Recorded in the same session.

### *D. Reflexes recorded from a single subject with an amputation of the left index finger*

### *Clinical presentation*

This lady sustained an injury to the left index finger at 11 years of age (now 29 years) which resulted in the amputation of the index finger to the P.I.P joint.

The cutaneomuscular reflex responses elcited following stimuation of the digital nerves of the stump of the index finger and little finger of the left hand in this individual are shown in figure 31. In both cases stimulation fails to elicit a reflex response from the left 1DI muscle.

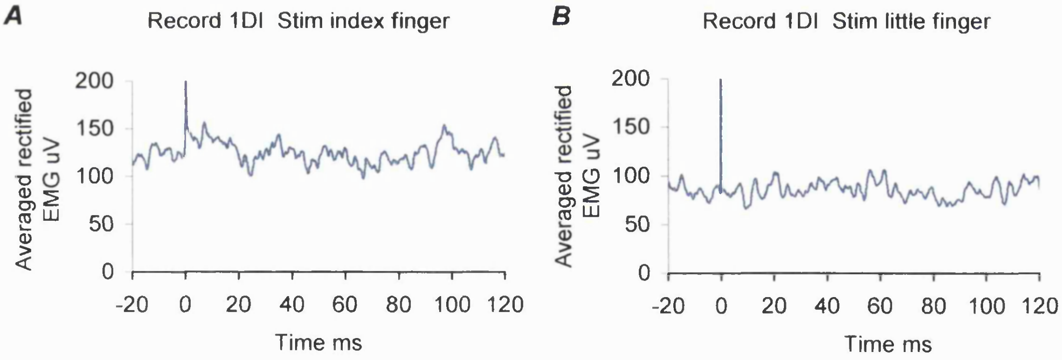


**Figure 31. Cutaneous reflex response recorded from 1DI following digital nerve stimulation of the index finger in an individual with a left index finger amputation to the P.I.P**

Cutaneomuscular reflex recorded from 1DI following stimulation of the digital nerves of (a) the index and (b) the little finger during a light sustained voluntary contraction of 1DI produced by performing abduction of the index finger at 10-20% MVC. *A,* No reflex response is evoked from the left 1DI following stimulation of the left index finger digital nerves. *B,* Stimulation of the left little finger digital nerves, evokes no reflex response. *A-B,* show the averaged rectified EMG time locked to each stimulus, presented at $5s^{-1}$. 250 sweeps. Recorded in the same session.

## Discussion

The present study has demonstrated that reflex cutaneomuscular responsiveness to stimulation of the digital nerves of the little finger is altered in subjects with carpal tunnel syndrome.

It was found that the E2 reflex component recorded from 1DI following stimulation of the digital nerves of the little finger was present in 62% of the trials obtained from the subjects with carpal tunnel syndrome compared to 13% of trials obtained from the healthy controls. The mean size of the E2 component recorded from the carpal tunnel subjects was found to be significantly larger when compared to the control subjects. The presence of the E2 reflex component following little finger digital nerve stimulation was found to be associated with mild but not moderate or moderate/severe entrapment of the median nerve.

It was also found that the size of the late E reflex component recorded from 1DI following little finger digital nerve stimulation was significantly larger in the carpal tunnel subjects compared to the healthy controls.

The E1, I1 & late I reflex components recorded from 1DI following little finger digital nerve stimulation in the carpal tunnel subjects were not found to be significantly different when compared to the size of the components obtained in the healthy controls.

In addition, the present study found that the size of the E1, I1 and E2 reflex components elicited following index finger digital nerve stimulation in the subjects with carpal tunnel syndrome was smaller when compared to the control subjects. The sizes of the late

I and E reflex components recorded from 1DI in the carpal tunnel syndrome subjects were not significantly different when compared to the control subjects.

### *Sensory volley to the CNS*

The present study found that the size of the sensory afferent volley recorded from the ulnar nerve at the wrist in the subjects with carpal tunnel syndrome was not significantly different when compared to the ulnar nerve SNAP recorded from the wrist in the healthy control subjects.

From these findings it is possible to exclude the possibility that the reflex responses recorded from 1DI following little finger digital nerve stimulation observed in the carpal tunnel syndrome subjects might be due to changes in the afferent input arriving at the spinal cord.

### *Clinical findings in the carpal tunnel syndrome subjects*

The present study found a preponderance of females and a mean age at presentation of 55.8 years. The distribution of the sensory symptoms described by the subjects in the present study varied from involving only the index and middle finger to involving all of the fingers and the palmar surface of the hand, symptoms rarely spread up the arm. These findings are concordant with other studies that have reported similar findings (D'Arcy & McGee, 2000; Stevens *et al.*1999).

Subjects with a moderate or moderate/severe median nerve entrapment were found to have a longer duration of symptoms, a higher pain rating and higher median nerve thresholds when compared to the subjects with a mild median nerve entrapment in the present study. Anderson *et al.* (1970) examined the histopathological changes that occur in median nerve entrapment in the guinea pig. It was found that in the early stages of median nerve compression, axonal conduction was slowed at the site of entrapment. As the duration of entrapment increased, histopathological examination of the median nerve showed evidence of demyelination/remyelination and axonal damage at the site of entrapment (Anderson *et al.* 1970). Therefore it is likely that the higher pain rating and median nerve thresholds experienced by the subjects in this study reflect the severity of the pathological changes occurring within the median nerve as a result of the entrapment.

### *Possible explanations for the reflex components elicited from 1DI following stimulation of the digital nerves of the little finger observed in the carpal tunnel subjects*

In the present study it was found that the E1 component was not significantly altered in the carpal tunnel subjects. This finding suggests, that in our subjects, any change resulting from the loss of median nerve afferent input secondary to the entrapment must have occurred at a level above the spinal cord, given that the E1 component reflects activities generated at a spinal level (Jenner & Stephens, 1982).

The present study found that the E2 component occurred more frequently and was significantly larger in the subjects with carpal tunnel syndrome. This finding supports the hypothesis of the present study, which suggested that loss of afferent inputs from the median nerve to S1 causes the cortical area within the primary somatosensory cortex responsive to the afferent inputs from territory of ulnar nerve to expand to encompass areas of the cortex previously devoted to the cutaneous afferent inputs from the median nerve. Thus resulting in reorganisation of S1.

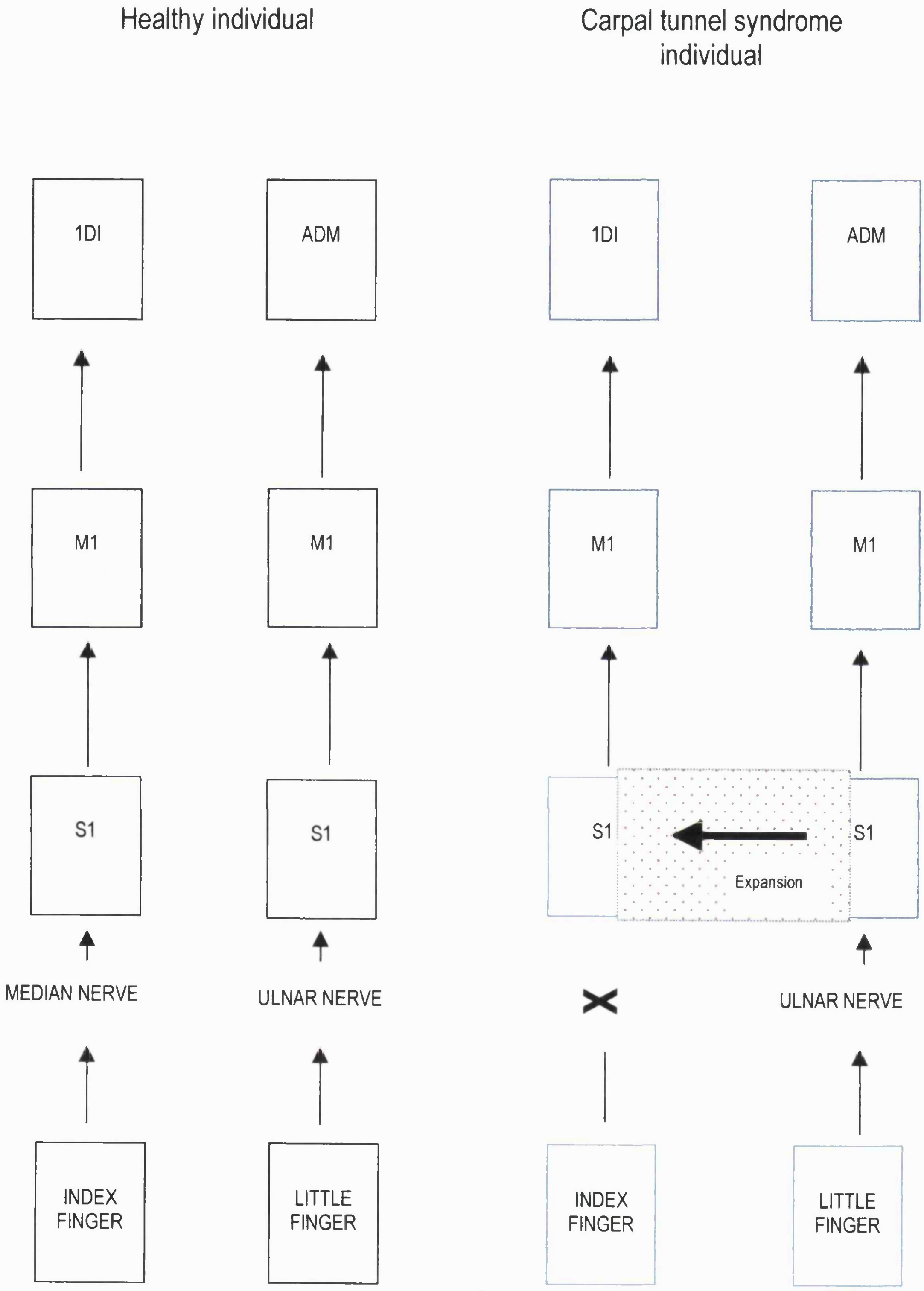
There is a large amount of evidence obtained from animal and human research suggesting that the somatosensory cortex undergoes reorganisation following an injury to a peripheral nerve (Kaas *et al.* 1983; Garraghty & Kaas, 1991*a*; Merzenich & Jenkins, 1993). In particular, Merzenich & Kaas (1982) demonstrated that a following a peripheral partial or complete section of the median nerve, the S1 reorganised. Injury triggered the adjacent undamaged cortical neurones (exclusive to the ulnar and radial nerve) to 'expand' into the regions previously responsive to the median nerve within the S1. Initially the expanded regions were silent but gradually after a period of approximately 1month, the expanded cortical neurones became responsive to the areas of skin previously exclusive to median nerve innervation territories. Other authors have reported similar findings (Wall *et al.* 1986; Calford & Tweedale, 1990; Garraghty & Kaas, 1991*a*).

In man, evidence suggesting that the S1 reorganises in response to the median nerve entrapment that occurs in CTS in man has been shown in a study by Halligan *et al.* (1993). The study described a subject with phantom limb sensations evoked by tactile stimulation of the face as previously described (Ramachandran, 1993) but whose resultant facial map was modified by pathology prior to amputation. The pathology was carpal tunnel syndrome. More recently Tinazzi *et al.* (1998) demonstrated that the N20/P25 cortical components of the somatosensory evoked potential following stimulation of the ulnar nerve were larger in subjects with CTS when compared to a group of normal subjects. The authors presumed that this was due to unmasking and changes in the amount of synaptic strength as a result of reorganisation within S1 in response to the CTS.

Therefore, it is possible to suggest that when the digital nerves of the little finger are stimulated in the carpal tunnel subjects of this study, afferent input generated by little finger stimulation is relayed to the reorganised S1 which now excites the S1 areas previously devoted to the median nerve territory, in addition to the regions devoted to the ulnar nerve territory. The afferent information in turn is relayed to M1 to produce the reflex effects are elicited from 1DI seen in the carpal tunnel subjects following little finger stimulation. This hypothetical model is illustrated in Figure 32.

The present findings do not however exclude the possibility that reorganisation may have occurred in the sub-cortical regions. Evidence suggests that reorganisation can occur within the dorsal column nuclei (DCN) (Pettit & Schwark, 1993) and in the VPL of the thalamus (Garraghty & Kaas, 1991*b*).

Subjects with carpal tunnel syndrome were also found to have a very long latency Late E component which occurred more frequently and which was significantly larger than the control subjects. It is difficult to define the origin of this component. As with the E2 component it is likely to be transcortical given the latency involved. It is unlikely to be a delayed E2 component as a number of the carpal tunnel syndrome subjects in the present study had both, an E2 component followed by a late E component. Further work is required to establish the nature of this component.



Healthy individual

Carpal tunnel syndrome individual

**Figure. 32 Hypothetical model for reorganisation in carpal tunnel syndrome**

**Healthy individual.** Stimulation of the digital nerves of the index finger elicits an afferent volley that is relayed via the ulnar nerve to S1, to M1 and then to 1DI, eliciting a reflex response. Similarly, when the digital nerves of the little finger are stimulated the afferent volley is relayed to S1, M1 and then to ADM, eliciting a reflex response.

**Carpal tunnel syndrome individual.** In these individuals, afferents from the median nerve are lost (shown as **X** on the illustration). Surmising that cortical regions previously devoted to the median nerve are taken over by the expansion of the intact cortical regions of the ulnar nerve (shown by dotted red box), stimulation of the digital nerves of the little finger will generate an afferent volley which is relayed to S1, causing the exciting the ulnar nerve regions as well as the areas previously devoted to the median nerve territory. The reorganised afferent information is relayed to M1 cortical regions devoted to both 1DI and ADM, which are then relayed to 1DI and ADM muscle, producing reflex effects.

The I1 component obtained from the subjects with carpal tunnel syndrome was not significantly different from the control subjects in the present study. As shown in this thesis and in other studies (Harrison *et al.* 2000), the I1 component appears to behave differently when compared to the E2 component, which is surprising considering that both components are transcortical in origin (Mayston *et al.* 1997). However this may be explained by differences in the route of the mediation of each of the components. As suggested earlier in this thesis, it is possible that the I1 component is mediated by via a direct pathway from the thalamus to M1 rather than a relay from the thalamus to S1 to M1.

### *The E2 reflex response and the association with mild entrapment*

It was found that the presence of the E2 component was associated with the subjects that had a mild but not moderate or moderate/severe median nerve entrapment. These findings are difficult to explain and require further investigation.

### *Possible explanations for the reflex components elicited from 1DI following stimulation of the digital nerves of the index finger in the carpal tunnel subjects*

The present study also found that the size of the reflex components recorded from 1DI following stimulation of the digital nerve of the index finger were significantly reduced when compared to the healthy controls. These findings can be explained by the loss of axons that occur in the median nerve as a result of the entrapment (Thomas & Fullerton, 1963; Anderson *et al.* 1970). Equally, it is also possible that conduction block of the damaged axons at the site of entrapment (Anderson *et al.* 1970) or temporal dispersion of the action potentials set up in the damaged axons (Kandel *et al.* 2000) may explain why the sizes of the reflex components are reduced.

*Other subjects studied*

The present study also showed that stimulation of the digital nerves of the right little finger in a single subject who had suffered a right median nerve transection elicited reflex components E1, I1 & E2 from 1DI, which were not evident when compared to healthy left hand. These findings suggest that in this subject, reorganisation may have occurred at spinal, sub-cortical or cortical regions as a result of disrupting the afferent input to S1.

The present study also presented results of a single subject that had suffered a left index finger amputation to the level of the P.I.P. Stimulation of either the stump of the index finger digital nerves or stimulation of the little finger failed to elicit any reflex components. These findings suggest in this subject, reorganisation has not occurred in response to the amputation.

## Conclusions

It is concluded that the E2 component associated with distant digital nerve stimulation of the little finger seen in subjects with CPNE reflects 'reorganisation' within the CNS, resulting from interruption of afferent input to the primary sensory cortex following median nerve entrapment.

The presence of the late E component with distant digital nerve stimulation most likely also reflects reorganisation within the CNS, in response to the entrapment but its significance remains less certain.

# Appendices

## *Appendix A: exclusion and inclusion criteria for subjects*

### *Exclusion criteria for control and carpal tunnel syndrome groups*

The participant should be excluded if a history of the following is elicited:

Peripheral neuropathy, e.g. diabetes
Neck injury/ trauma
Neurological disease
Rheumatic disease
Falling outside of the age range selected for the study

### *Inclusion Criteria for control and Carpal tunnel syndrome groups*

Warm Hands
Age range 18-80 years
Mixed gender

### *Inclusion Criteria for Control group*

In addition to the exclusion criteria set for the control and carpal tunnel subjects, the control group was recorded from healthy adult subjects free from any of the clinical symptoms of carpal tunnel syndrome.

### *Inclusion Criteria for Carpal tunnel syndrome group*

Subjects with suspected carpal tunnel syndrome (CTS) under went sensory and motor nerve conduction studies prior to participation. Once the diagnosis was established, the severity of the entrapment was graded (performed by the resident consultant Neurophysiologist) according to the electrophysiological findings described in appendix B.

# *Appendix B: Grading the severity of carpal tunnel syndrome*

Each subject was graded into mild, moderate, severe or end-stage carpal tunnel syndrome (CTS) according to the electrophysiological changes in the sensory and motor nerve conduction studies. The criteria used to grade CTS are shown in the table below.

| **Grade of CTS** | **Sensory action nerve potential (SNAP)** | **Distal motor latency (DML)** | **Muscle action potential (MAP)** | **Conduction velocity (CV)** |
|---|---|---|---|---|
| **Mild** | palm to wrist > 0.2ms<br>median > 0.5ms than ulnar SNAP | normal ~4.0ms | normal usually 5-10mV | median > 5-6$ms^{-1}$ than ulnar SNAP<br>MAP recorded from APB normal (> 45$ms^{-1}$) |
| **Moderate** | absent | delayed > 4.5ms | normal or slight reduction in mV | MAP recorded from APB may be slowed (< 45$ms^{-1}$) |
| **Severe** | absent | delayed >8 –10ms | < 4.0mV | MAP from APB can be normal but more likely slowed (=/ < 40$ms^{-1}$) |
| **End stage** | absent | ? | Absent or <0.5mV | ? |

## *Appendix C: Carpal tunnel syndrome questionnaire regarding symptoms*

***How long have you had the symptoms?***

***Do you suffer from:***

Pins/needles?

Numbness?

Pain?

***How would you rate your pain (0 = no pain 10 = the worst possible pain)?***

***When do you suffer these symptoms:***

On waking?

During the day?

At night?

***Where are the symptoms ?***

Thumb

Index finger

Middle finger

Ring finger

Little finger

Any other region (please state)

***Do you find any tasks involving the hands difficult to carry out?***

***Additional notes***

Any evidence of muscle wasting of thenar muscles?

Tinel's sign?

Thresholds

*Median nerve*

*Ulnar nerve*

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# Finger movement attenuates cutaneomuscular reflexes recorded from the first dorsal interosseous muscle in man

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Cutaneomuscular reflex responses (CMR) typically comprise three components, an E1 spinal component followed by supraspinal components, I1 and E2 (Mayston *et al.* 1997). Previous studies have shown that CMRs are dependent upon the ongoing motor task (Evans *et al.* 1989), exhibit habituation (Harrison *et al.* 2000) and can be modulated during acquisition of a new motor skill (Nadler *et al.* 2000). In this study we report attenuation of the transcortical E2 component of the CMR during finger movement.

With ethical approval and informed consent, surface EMG was recorded from the first dorsal interosseous muscle (1DI) of the preferred hand, sensory evoked potentials (SEP) were recorded from the contralateral sensory cortex and the sensory nerve action potential (SNAP) was recorded from the median nerve of fifteen adult subjects whilst electrically stimulating the digital nerves of the index finger (2.5 times sensory threshold, 100 µS, 5 Hz). Subjects performed the following tasks twice in random order: *(a)* a sustained abduction of the index finger against resistance at 10-20 % maximum voluntary contraction (Abd), and *(b)* abduction of the index finger as in *(a)* whilst performing self-paced low amplitude tapping of the (i) index finger (Abd + I), (ii) thumb (Abd + T), (iii) middle finger (Abd + M) and (iv) little finger (Abd + L). EMG was rectified. EMG, SNAP and SEP were averaged time-locked to the stimulus for 250 sweeps.

CMR component size, expressed as % EMG modulation, was measured as described by Nadler *et al* (2000). Data were analysed using repeated measures ANOVA. The size of the SNAPs was independent of task. CMR data are summarised in Fig. 1. The E2 component was significantly reduced during finger tapping ($P < 0.05$) and this reduction was independent of which finger was tapping ($P > 0.05$). There were no significant changes in E1 and I1 ($P > 0.05$). The N20-P25 of the SEP was significantly reduced in amplitude during finger tapping compared with Abd ($P < 0.05$). We conclude that the decrease in size of the E2 component associated with finger tapping results from gating of the digital nerve input.

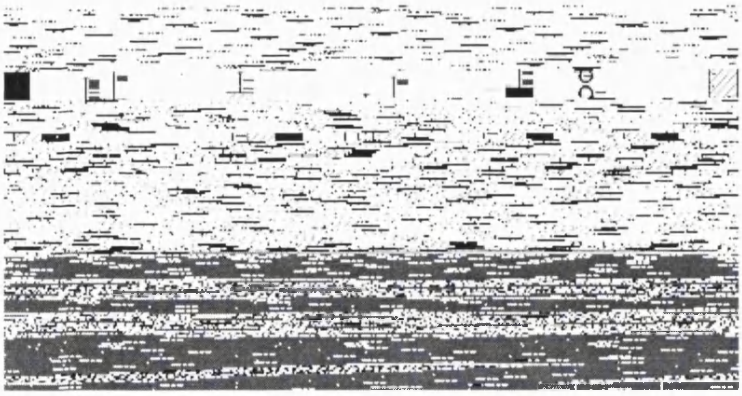

Figure 1. The effect of finger movement upon the E1 (☐), I1 (▨), and E2 (■) components of the CMR in all subjects. Data are means ± 1 S.E.M.

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# Finger movement is associated with attenuated cutaneous reflexes recorded from human first dorsal interosseous muscle

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Cutaneomuscular reflexes (CMR) have been recorded from the first dorsal interosseous muscle (1DI) of the preferred hand, somatosensory evoked potentials (SEP) were recorded from the contralateral sensory cortex and the sensory nerve action potential (SNAP) was recorded from the median nerve of 15 adult subjects whilst electrically stimulating the digital nerves of the index finger. Subjects performed the following tasks (a) a sustained abduction of the index finger against resistance at 10–20 % maximum voluntary contraction (MVC), and (b) abduction of the index finger as in (a) whilst performing self paced low amplitude tapping of the (i) index finger, (ii) thumb, (iii) middle finger, (iv) little finger and (v) ipsilateral foot. The E2 component of the CMR and the N20/P25 components of the SEP were significantly reduced during finger tapping ($P < 0.05$). This reduction was independent of which finger was tapping ($P > 0.05$). There was a significant (qualitative) relationship between the decrease in the size of the E2 component of the CMR and the N20/P25 components of the SEP ($\chi^2$ test; $P < 0.05$). There were no significant changes in E1 and I1 ($P > 0.05$). The size of the SNAP was independent of task ($P > 0.05$). The size of the E1, I1, E2 components of the CMR, and the N20/P25 components of the SEP were unaltered during foot tapping ($P > 0.05$, $n = 4$). We conclude that the decrease in size of the E2 component associated with finger tapping results from gating of the digital nerve input.

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Cutaneomuscular reflexes (CMR) can be evoked by modest, non-painful electrical stimulation of the digital nerves of the finger producing a reflex modulation of the ongoing muscle activity (EMG) recorded during a sustained voluntary contraction of an intrinsic hand muscle (Caccia *et al.* 1973; Jenner & Stephens, 1982). The CMR recorded from the first dorsal interosseous muscle (1DI) following stimulation of the digital nerves of the index finger is typically triphasic in appearance; there is an initial increase of EMG, (E1) followed by a decrease, (I1), followed by a prominent second increase, (E2). Evidence suggests that the E1 component is mediated via oligosynaptic spinal circuitry (Jenner & Stephens, 1982). The E2 component is mediated via a transcortical pathway, requiring the integrity of the dorsal columns, sensorimotor cortex and the corticospinal tract (Carr *et al.* 1993; Mayston *et al.* 1997). Recent findings also suggest that the I1 component is mediated via a transcortical pathway (Mayston *et al.* 1997).

The reflex effects of cutaneous stimulation on a given muscle are known to depend upon the task being carried out when the reflex is elicited. In the first dorsal interosseous muscle for example, the transcortical E2 component of the CMR evoked by stimulating the digital nerves of the index finger is greater when the subject performs a isolated finger abduction than when the muscle is active during the combined movement of all of the fingers, as in a power grip (Evans *et al.*1989).

Somatosensory evoked potentials (SEP) represent the afferent volley evoked by the electrical stimulation of a digital or mixed nerve as it is propagated along the somatosensory pathway to the primary sensory cortex (S1). The SEP is made up of a number of distinct components that reflect activities from different generators. The N20/P25 SEP components recorded from electrodes attached to the scalp over the contralateral sensory cortex are thought to reflect cortically generated activities within the S1. Current evidence suggests that the N20 component represents afferent activity arriving at Brodmann's 3b area. The P25 component is believed to reflect further processing of the afferent activities at Brodmann's area 1 (Desmedt & Tomberg, 1989).

It is well established that cutaneous afferent input to the S1 is attenuated or 'gated' during movement (Giblin, 1964; Rushton *et al.* 1981; Cheron *et al.* 2000). In man SEP recordings obtained directly from exposed cortex and the scalp have been used to provide evidence that the largest amount of 'gating' occurs at a cortical level (Cheron & Borenstein, 1987; Hsieh *et al.* 1995), whilst the least amount of 'gating' occurs at brainstem level (Hsieh *et al.* 1995).

With this background in mind, in the present study we have examined the effect of performing concurrent small phasic movements of a finger upon the size of the CMR recorded from the 1DI evoked by electrical stimulation of the digital nerves of the index finger during a sustained voluntary contraction of 1DI at 10–20 % of MVC, whilst simultaneously recording the SEP from the contralateral sensory cortex. Evidence is presented which suggests that the decrease in the size of the E2 component of the reflex reported in the present study in association with finger tapping results from 'gating' of the digital nerve input at a level above the spinal cord, most likely within the cortex. A preliminary account has been presented to The Physiological Society (Turner *et al.* 2001).

## METHODS

### Subjects

Cutaneomuscular reflexes, digital nerve somatosensory evoked potentials, and sensory nerve action potentials were recorded from the preferred hand of 15 healthy subjects, aged 17–49 years (six female). All subjects gave informed consent. The experimental protocols were approved by the local ethics committee, and were in accordance with the guidelines set out in the Declaration of Helsinki, 1964.

### Cutaneomuscular reflexes

Reflexes were recorded from the first dorsal interosseous muscle. The surface EMG was recorded using self-adhesive electrodes (TECA NCS Disposable Surface Electrodes, Oxford Instruments Medical, Old Woking, UK) that were placed on the skin over the belly of the muscle, inter-electrode distance 2.5 cm. The subject was asked to abduct the index finger against resistance at 10–20 % maximal voluntary contraction (MVC) using an LED root mean square voltmeter as a visual aid. The EMG was amplified, filtered (20 Hz–5 KHz, Oxford Instruments Medical, Sapphire 4ME) and stored on magnetic tape for future analysis (Racal, Store 4, Southampton, UK).

### Digital nerve somatosensory evoked potentials

Recordings were made from the sensory cortex contralateral to the side of stimulation. The scalp was prepared using skinpure abrasive paste (Unimed Electrode Supplies, Farnham, UK). Stick-on silver/silver chloride disc electrodes (10 mm stick-on EEG electrodes, Oxford Instruments Medical) were placed onto the scalp using an adhesive conductive EEG paste (Ten20, Unimed Electrode Supplies). The active electrode was positioned 2.5 cm behind Cz (International 10–20 System) and 7 cm laterally. A reference electrode was placed onto the earlobe ipsilateral to the side of stimulation (Tomberg *et al.* 1991). The ongoing EEG was amplified, filtered (20 Hz–2 KHz, Sapphire 4ME) and stored on magnetic tape (Racal, Store 4) for further analysis.

### Sensory nerve action potentials

Sensory nerve action potentials were recorded using surface electrodes placed onto the skin overlying the median nerve at the wrist (TECA NCS Disposable Surface Electrodes, Oxford Instruments Medical). The SNAP was amplified (20 Hz–2 KHz, Sapphire 4ME) and stored on magnetic tape (Racal, Store 4) for analysis.

### Digital nerve stimulation

The digital nerves of the index finger were electrically stimulated using ring electrodes (Oxford Instruments Medical), which were placed either side of the proximal interphalangeal joint. The stimulus was delivered using a constant current stimulator (Sapphire 4ME) at a level 2.5 times above that required for perception (pulse duration 100 $\mu$s, frequency 5 Hz). The perception threshold was determined while the subject's hand was relaxed.

### Experiment 1

Cutaneomuscular reflexes, digital nerve somatosensory evoked potentials and sensory nerve action potentials were recorded, following digital nerve stimulation of the index finger. Subjects performed the following finger movement tasks: (a) a sustained voluntary abduction of the index finger at 10–20 % MVC using a LED voltmeter as visual feedback, and (b) abduction of the index finger as in (a) whilst simultaneously performing concurrent small self-paced tapping of the (i) index finger, (ii) thumb, (iii) middle finger and (iv) little finger. For each experimental run, subjects were asked to maintain the LED voltmeter monitoring 1DI EMG lit to the 10–20 % MVC level. In the case of the index finger (b)(i) subjects abducted the index finger to the 10–20 % MVC level. Once achieved, subjects were instructed to make small concurrent tapping movements of the index finger throughout the period of digital nerve stimulation. The experimenter carefully monitored the subject and LED voltmeter EMG levels to ensure that the subject continued to abduct whilst performing the movement task.

All subjects performed the finger movement tasks twice, and in a random order. Subjects rested for a few minutes between each task. Data were excluded if the subject was unable to perform the task, or produced a large amount of wrist movement making it impossible to record the afferent volley at the wrist.

### Experiment 2

Cutaneomuscular reflexes, digital nerve somatosensory evoked potentials and sensory nerve action potentials were recorded, following digital nerve stimulation of the index finger. In the second experiment four subjects from experiment 1 were asked to abduct the index finger as (a) in experiment 1 whilst simultaneously performing self-paced tapping of the ipsilateral foot.

### Analysis

**Cutaneomuscular reflexes.** The amplified and filtered EMG signal was rectified and then averaged time-locked to the stimulus for 250 sweeps (SigAvg program; Cambridge Electronic Design, Cambridge, UK). The size of each of the reflex components E1, I1 and E2 was expressed in terms of percentage modulation of background EMG (Nadler *et al.* 2000). The mean level of ongoing background EMG was found from a 20 ms pre-stimulus period of EMG. A component was considered present if it rose above or fell below the 95 % confidence level of the mean EMG for at least 8 ms (Wohlert, 1996). Because each finger movement task was performed twice in the same recording session, the mean percentage modulation was calculated for each component from the two recordings by taking the percentage modulation measured for each of the 250 sweeps. This was performed for each finger movement task in all subjects.

**Digital nerve somatosensory evoked potentials.** The ongoing amplified and filtered EEG signal was averaged time-locked to the stimulus for 250 sweeps. The size of the SEP recorded following electrical stimulation of the digital nerves is particularly small. To improve the signal to noise ratio the two 250 sweep averages were combined using the SigAvg program to give a singe 500 sweep average for each finger movement task. The peak-to-peak amplitude of the N20/P25 components was measured.

**Sensory nerve action potentials.** The amplified and filtered signal was averaged time-locked to the stimulus for 250 sweeps (SigAvg program). The size of the SNAP was found by measuring the peak-to-peak amplitude.

### Statistical analysis

The effect of finger tapping on the size of the CMR, SEP and SNAP was examined by performing repeated measures analysis of variance (rmANOVA). The $\chi^2$ test for association with Yates continuity correction was also employed. Any significant association was further verified by employing Fisher's exact method. The level of statistical significance was set at $P < 0.05$.

## RESULTS

Figure 1 shows the effect of simultaneously making a finger movement on the averaged rectified EMG recorded from 1DI during a sustained voluntary abduction of the index

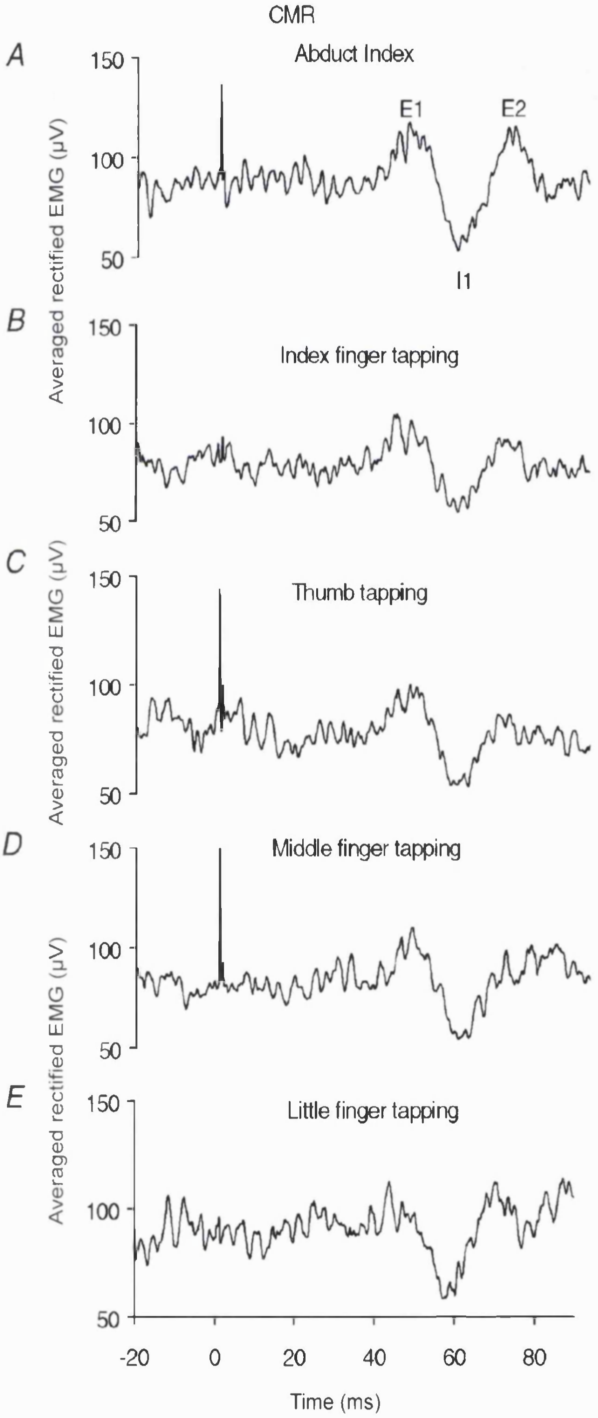

**Figure 1. Effect of finger movement on the components of the CMR recorded from 1DI following electrical stimulation of the digital nerves of the index finger**

*A*, cutaneous reflex response recorded from 1DI following stimulation of the digital nerves of the index finger during a sustained voluntary abduction of the index finger, maintained at 10–20 % of the MVC (Abd). A clear cutaneous reflex was observed consisting of an initial rise, E1, followed by a decrease, I1, followed by a second increase, E2, (labelled on the trace). *B–E*, reflex recorded from 1DI following stimulation of the digital nerves of the index finger during a sustained voluntary abduction of the index finger maintained at 10–20 % of the MVC as in *A* with concomitant tapping of: *B*, the index finger (Abd + I); *C*, the thumb (Abd + T); *D*, the middle finger (Abd + M); and *E*, the little finger (Abd + L). In each case the reflex component E2 is clearly reduced or abolished in the case of middle finger tapping whilst E1 and I1 remain unaltered. *A–E*, show the rectified and averaged EMG time locked to each stimulus, delivered at 5 s$^{-1}$. 250 sweeps. All recorded in the same session.

finger for one subject. During simple index finger abduction (Fig. 1*A*) without simultaneous finger tapping, the stimulus clearly elicits three components; a short latency increase in EMG, E1, followed by a decrease, I1, followed by a second increase, E2, producing per cent EMG modulations of 15.5, 19.2 and 19.5 respectively. In contrast, when this subject performs self-paced tapping of the index finger whilst simultaneously abducting the index finger, there is a clear reduction in the size of the E2 modulation, decreasing from 19.5 to 6.1. The E1 and I1 modulations are unaltered producing per cent EMG modulations of 17.6 and 16.9 respectively. This is shown in Fig. 1*B*. There are similar effects when the individual performs self-paced tapping of the thumb, middle and little finger (Fig. 1*C–E*). The size of the E2 component produced by index finger abduction is clearly reduced in all tasks. The per cent EMG E2 modulations produced are 6.0, 0.0 and 12.2 respectively. The E1 and I1 modulations are unchanged producing per cent EMG modulations of 16.9, 21.3 and 15.4 respectively for the E1 component, and 19.7, 16.9 and 14.6 respectively for the I1 component. The size of the sensory volley recorded from the median nerve during the finger movements

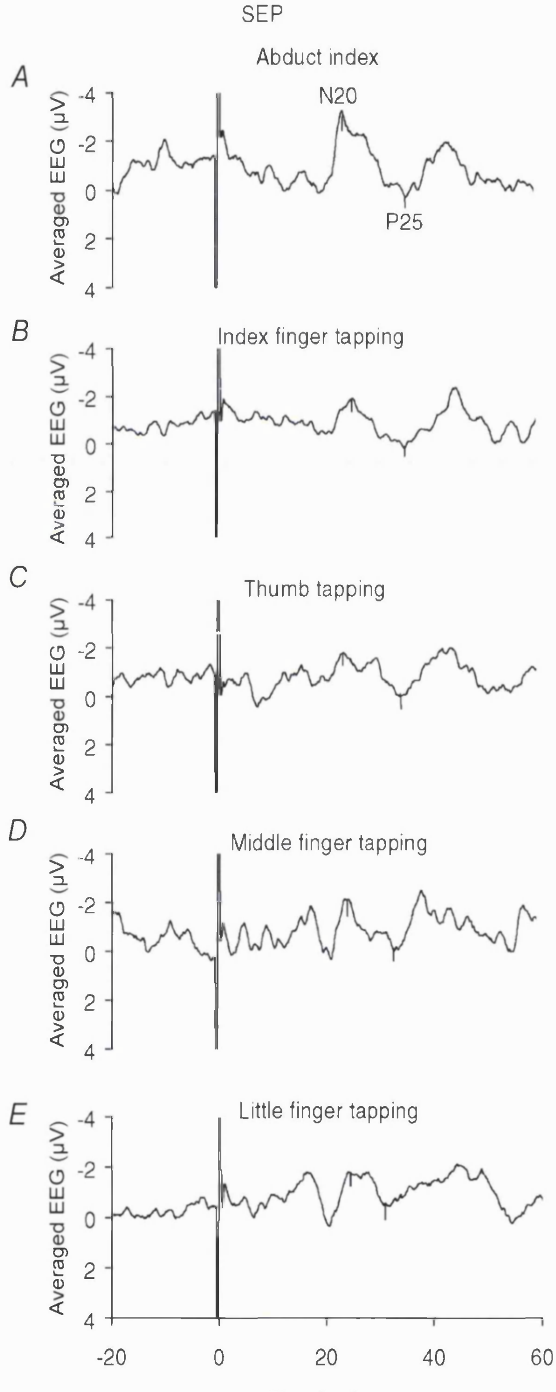

**Figure 2. Effect of finger movement on the N20/P25 components of the SEP recorded from the contralateral sensory cortex following electrical stimulation of the digital nerves of the index finger**

*A*, N20/P25 response recorded from the contralateral sensory cortex following stimulation of the digital nerves of the index finger during a sustained voluntary abduction of the index finger, maintained at 10–20 % of the MVC (Abd). An initial negative rise, N20, followed by a positive decrease, P25, was seen, (labelled on the trace). *B–E*, N20/P25 response recorded from the contralateral sensory cortex following stimulation of the digital nerves of the index finger during a sustained voluntary abduction of the index finger maintained at 10–20 % of the MVC as in *A* with concomitant tapping of: *B*, the index finger (Abd + I); *C*, the thumb (Abd + T); *D*, the middle finger (Abd + M); and *E*, the little finger (Abd + L). In each case the response is clearly reduced. *A–E*, show the averaged EEG time-locked to each stimulus, delivered at 5 $s^{-1}$. 500 sweeps (a 250 sweep average was obtained on two occasions in the same recording session and combined to give a 500 sweep average).

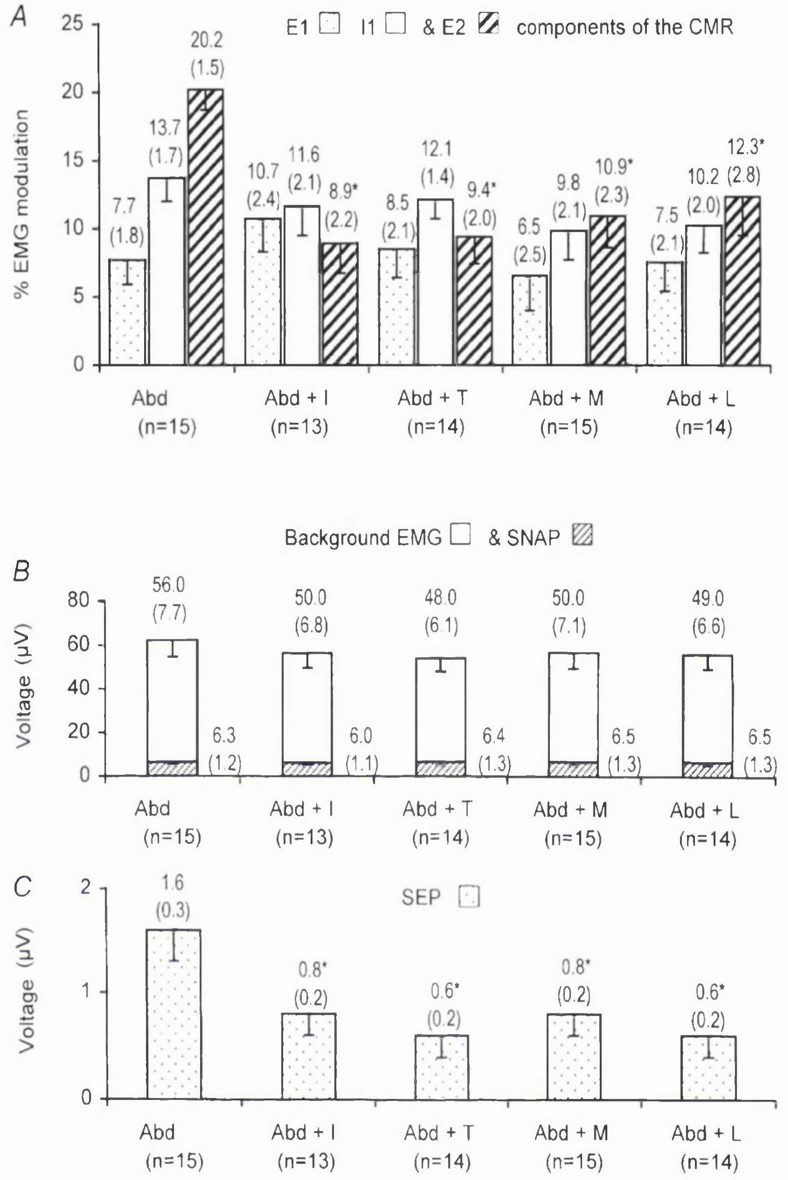

**Figure 3. Mean data (–1 S.E.M.) obtained from all subjects showing the effect of finger tapping upon the CMR, SEP, SNAP and EMG**

Mean size of each component (top) and S.E.M. (bracketed) are given above each bar for each chart. *A*, CMR recorded from 1DI, following stimulation the of the index finger digital nerves during a sustained abduction of the index finger alone (Abd) contrasting the CMR obtained during index finger (Abd + I), thumb (Abd + T), middle finger (Abd + M) and little finger (Abd + L) tapping. Stippled bars: mean size of E1 component. Open bars: mean size of the I1 component. Hatched bars: mean size of the E2. component Significant differences were found in the size of the E2 component on comparing the differences between the means obtained during abduction and each finger movement (rmANOVA, $P < 0.05$, denoted *). Components E1 and I1 were not significantly altered (rmANOVA, $P > 0.05$ in both cases). *B*, SNAP recorded from the median nerve at the wrist and background EMG recorded from IDI during index finger abduction following electrical stimulation of the index finger digital nerves for each finger tapping task performed as described in *A*. Hatched bars: mean size of the SNAP recorded from the median nerve. Open bars: mean size of the background EMG. *C*, SEP recorded from the contralateral sensory cortex, following electrical stimulation of the index finger digital nerves whilst performing a sustained voluntary abduction of the index finger compared to the effect of abducting the index finger with concomitant tapping of the finger as described in *A*. Stippled bars: mean size of the N20/P25 component of the SEP. Significant differences in the size of the N20/P25 components were found on comparing the means obtained during abduction and each finger movement (rmANOVA, $P < 0.05$, denoted *).

ranged from 3.0–3.4 $\mu$V peak-to-peak. The background EMG level during each of the finger tapping movements ranged from 79–88 $\mu$V.

Taking all the data together, the mean size of the E2 component decreased when finger tapping was performed whilst simultaneously abducting the index finger in 91 % of all recordings (Fig. 3*A*). Repeated measures analysis of variance (rmANOVA) revealed a significant decrease in the size of the E2 component recorded from 1DI during a sustained abduction of the index finger whilst simultaneously performing finger tapping compared to the size of the E2 component when simply abducting the index finger ($P < 0.05$ for each finger tapping movement task). Of the 15 subjects, 73 % reported a decreased appreciation of the stimulus during tapping compared with abduction alone. Although the mean size of the I1 component was reduced particularly during little and middle finger tapping this change was not found to be statistically significantly different to index finger abduction ($P > 0.05$). The E1 component was unaltered during finger tapping ($P > 0.05$).

On first inspection of the chart illustrated in Fig. 3*A*, it appears that there is a graded effect in the decrease in the size of the mean per cent E2 EMG modulation. The maximal decrease in the size of the E2 component appears to occur when performing index finger or thumb tapping, whilst little finger tapping appears to have the least effect. However rmANOVA did not reveal a significant difference between which finger was performing the tapping and the resultant decrease in the size of the mean per cent E2 EMG modulation ($P > 0.05$).

The size of the afferent volley recorded from the median nerve at the wrist and the background EMG levels are shown in Fig. 3*B* for all subjects. It was found that finger tapping did not significantly alter the afferent volley to the spinal cord ($P > 0.05$) or background EMG ($P > 0.05$).

Figure 2 shows the simultaneously recorded SEP obtained from S1 following stimulation of the digital nerves of the index finger in one subject. When the subject performs a simple abduction of the index finger (Fig. 2*A*), approximately 20 ms following stimulation there is an initial negative rising component, N20, followed by a positive down going component, P25. The peak-to-peak amplitude of the N20/P25 components measured 2.7 $\mu$V. However when the subject performs tapping of a finger whilst simultaneously abducting the index finger there is a clear reduction in the size of the N20/P25 components (Fig. 2*B–E*). The measured peak-to-peak amplitudes being 1.3 $\mu$V during index tapping, 1.9 $\mu$V during thumb tapping, 1.8 $\mu$V during middle and 1.3 $\mu$V during little finger tapping.

Combining all data together, the mean size of the amplitude of the N20/P25 components is significantly reduced by finger tapping when compared to simple abduction of the index finger (rmANOVA, $P < 0.05$ in all finger movements). This is illustrated in Fig. 3*C*. As with the CMR, pairwise comparisons failed to show that the decrease in the size of the N20/P25 components was dependent upon which finger was tapping ($P > 0.05$).

The $\chi^2$ test for association performed upon the combined data showed a significant qualitative relationship between the decrease in the size of the E2 component of the CMR and the decrease in the size N20/P25 components of the SEP ($P < 0.05$). Given the small study sample the significance was verified by employing the Fisher's exact method ($P < 0.05$).

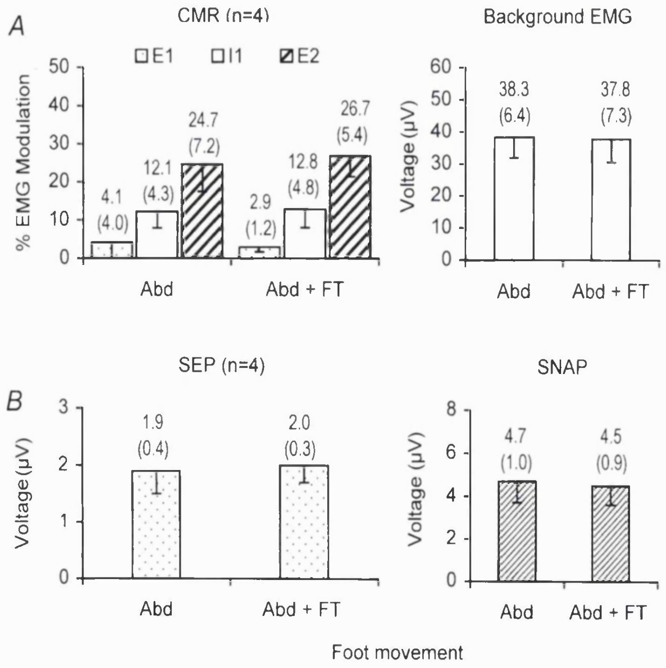

**Figure 4. Mean data (–1 S.E.M.) obtained from four subjects showing the effect of ipsilateral foot tapping on the components of the CMR, background EMG, SEP and SNAP**

Mean data value (top) and S.E.M. (bracketed) are shown on the chart above each bar. *A*, CMR and background EMG recorded from 1DI, whilst stimulating the digital nerves of the index finger during sustained abduction of the index finger alone (Abd) contrasting the CMR obtained during foot tapping (Abd + FT). Stippled bars: mean size of the component E1 of the reflex. Open bars: mean size of the I1 component of the reflex. Hatched bars: mean size of the component E2 of the reflex. Open bars (right bar chart): mean size of the background EMG. *B*, SEP recorded from the contralateral sensory cortex and SNAP recorded from the median nerve at the wrist. Stippled bars: mean size of the N20/P25 component of the SEP. Hatched bars: mean size of the afferent volley.

Figure 4 shows the effect of concurrently tapping the ipsilateral foot whilst simultaneously abducting the index finger upon the CMR and SEP for all subjects ($n = 4$). Taking the data as a whole, the mean size of the E1, I1, E2 components of the CMR and the N20/P25 components of the SEP are unaltered when concurrently tapping the ipsilateral foot in 100 % of all recordings. The size of the components of the CMR recorded from 1DI and the sensory cortex during index finger abduction whilst concurrently tapping the foot showed no significant change when compared to the size of the components of the CMR and SEP recorded when simply abducting the index finger (rmANOVA, $P > 0.05$ in all cases). This was similarly the case for the SNAP and background EMG levels ($P > 0.05$ in both cases) also illustrated in Fig. 4.

## DISCUSSION

The present study has demonstrated that the E2 component of the CMR recorded from the 1DI muscle is reduced when finger tapping is performed. The reduction in the size of the E2 component was found to be unrelated to which finger is tapping. This effect on the E2 component of the CMR is not seen when ipsilateral foot tapping is performed in place of finger tapping. The E1 and I1 components were found to be unchanged during either finger or foot tapping. It has also been shown that the reduction in the size of the E2 component seen during finger tapping is associated with a reduction in the size of the N20/P25 components of the SEP, reflecting the activities within areas 3b and 1 generated within the S1 in response to the afferent input (Desmedt & Tomberg, 1989).

This decrease in the size of the E2 CMR and N20/P25 SEP components cannot be due to a change in the afferent input to the spinal cord as the size of the SNAP recorded from the wrist was not significantly altered during finger tapping.

The E1 component was unaltered during finger tapping, suggesting that the decrease seen in the present study must have occurred at a level above the spinal cord, as evidence suggests that E1 (Jenner & Stephens, 1982) is spinal whilst I1 and E2 components of the reflex are transcortical in origin (Mayston *et al.* 1997).

The present findings have shown that during finger tapping there is a significant decrease in the size of the E2 component of the CMR in association with a decrease in the size of the N20/P25 SEP components at the S1. These findings are concordant with the notion that the decrease in the size of the E2 component of the CMR is due to 'gating' of the afferent input during finger tapping. Indeed 73 % of the subjects in the present study reported a decreased awareness of the stimulus during tapping compared with abduction alone. There are a number of reports showing 'gating' of afferent information at different sites as it is propagated along the somatosensory pathway during movement. In animals 'gating' has been shown within the DCN (Ghez & Pisa, 1972), thalamus within VPN (Tsumoto *et al.* 1975) and S1 (Chaplin & Woolward, 1981). However in man, 'gating' of the afferent information is believed to occur within S1 with little contribution from the sub-cortical regions of the brain (Rushton *et al.* 1981; Hsieh *et al.* 1995). This suggests that the reduction in the size of the N20/P25 SEP components most likely reflects 'gating' of the afferent information within S1.

However Palmeri *et al.* (1999) have recently demonstrated that the motor cortex (M1) is also able to exert effects on the afferent activity at the level of the DCN and VPN during limb movement in cats. Therefore it is possible that the reduction in the size of the afferent volley arriving at S1 seen in the present study may reflect 'gating' of the afferent information within the DCN/VPN imposed by M1 during movement as opposed to S1.

There is also evidence that 'gating' of afferent information can be mediated by sensory feedback (Cheyne *et al.* 1997) as well as corollary discharges to other motor regions when a voluntary movement is initiated (Paus *et al.* 1996). Thus in the present experiments proprioceptive feedback from the finger movement and cutaneous afferent input generated by the tap may also play a part in the 'gating' process. It is likely that both mechanisms contribute to the 'gating' effect. How much of a role each mechanism plays could be tested by performing passive finger tapping in place of active finger movement, leaving the sensory feedback but removing the corollary discharge. The role of proprioceptive feedback and cutaneous afferent input could be explored by carrying out experiments in which the fingertips are anaesthetised.

Complementary studies in which four subjects performed ipsilateral foot tapping whilst abducting the index finger showed no reduction in the size of the E2 CMR component or N20/P25 SEP components in the present study. This finding provides evidence that the reduction in the size of the CMR and digital nerve SEP, which occurs during finger tapping, is not unspecific, although further experiments are required to see if less remote areas of the body such as the arm or ipsilateral hand could produce similar effects to the finger tapping performed in this study.

Given the transcortical origin of the I1 and E2 components of the CMR (Mayston *et al.* 1997) it is surprising that finger tapping did not alter the size of the I1 component of the reflex. Increasingly it has become apparent that the I1 has different characteristics to the E2 component of the CMR. Harrison *et al.* (2000) have demonstrated that the I1 component shows little habituation in comparison to the

E2 component, which habituates much more readily. One possible explanation for these findings may relate to differences in the route of mediation of each component.

In conclusion, the present study has demonstrated that during finger tapping there is a significant decrease in the size of the E2 component of the CMR that is associated with a decrease in the size of the N20/P25 SEP components. The most likely explanation for these findings is that the decrease in the size of the E2 component results from 'gating' of the afferent information within the sensory cortex during finger tapping.

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