REFLEX CONTROL OF
HUMAN TRUNK MUSCLES

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ABSTRACT

Muscles of the human trunk are arranged in layers and attach either to the vertebral column or to the pelvis and thorax. Present understanding suggests the deeper muscles, attached to the vertebral column, stabilise the spine, whereas the more superficial muscles, attached to the thorax and pelvis, produce and control trunk movement. If so, the control of these two groups may differ, with deeper muscles working synergistically and those more superficially located acting antagonistically to one another. To this end the role that reflex connections between the different muscles may play in mediating either synergistic or antagonistic roles was investigated.

Muscle afferent activity was evoked via a series of mechanical taps applied to individual muscle/tendon complexes of three abdominal and two paraspinal muscles by means of a mechanical tapping device. The resultant reflex responses were recorded by surface electromyography in the same five muscles, both ipsilateral and contralateral to the applied tap. This allowed analysis of the effect of muscle afferents from any one muscle to all the others.

Short latency, (less than 25ms) heteronymous muscle afferent connections are excitatory and widespread between the abdominal muscles. They are also excitatory between ipsilateral paraspinal muscles, but inhibitory between these muscles contralaterally. Reflexes are mostly absent between abdominal and paraspinal muscles. Specifically, connections both to and from the internal oblique muscle (IO), the deepest abdominal muscle studied, were the most widespread and potent, with the connection from one IO to the other being of similar amplitude and minimal difference in latency. It is suggested that at least the earliest part of the short latency excitatory crossed reflexes observed here, are monosynaptically mediated. In addition, there is evidence of asymmetry in the presence and strength of these reflexes between the left and right sides. Longer latency reflexes with latencies of between 40 and 50ms were also observed between all muscle groups studied. These were excitatory within the abdominal and paraspinal groups, but inhibitory between them. However, whether these originate from muscle or cutaneous afferents is unclear.
ACKNOWLEDGEMENTS

I wish to thank Dr Philip Harrison for supervising me throughout this process and for initially highlighting the need to study the reflex control of trunk muscles. It has been good to observe at such close hand and learn the process of scientific investigation, from one so able. I also thank Professor John Stephens for being there when I needed him as my second supervisor. These acknowledgements would not be complete without reference to Caroline Alexander my fellow PhD student. Working together in the same research group has inevitably provided peer support, and that has been invaluable and good fun. Many others have also supported me through this process. At King College London my enduring thanks to go to Professor Di Newham for being there and believing I could do this, to Peter Milligan for patience and to Bob Roberts, for patience and technical support. Numerous colleagues have also been there. This has been most obvious in the coffee room with Claire White, Duncan Critchley, Heather Holder Powell, and Joan McMeeken. In addition Phil, Caroline and Matt Morrisey read and commented on full version of the thesis, God Bless you all. Other colleagues who have listened patiently include Mike Hurley, Olga Rutherford, and Sheila Kitchen among many. I would also like to acknowledge the help and support of Mr John O'Dowd in gaining the financial support of the Arthritis Research Campaign. Many people outside the academic environment including my family and my in-laws have also listened with great patience especially in the last six months when I really have had nothing to else to talk about but trunk muscle reflexes. Maybe those who I have not been able to keep up with regularly haven’t missed much.

However, there is one person who has endured more than any other, probably more than I will ever know, and that is my wife Avril. Words cannot express my appreciation. Thank you.

Postscript
The viva voce to examine this thesis was held on 20th June 2002. On that day my father was admitted to hospital, and when I saw him there that evening he was very proud to be told I had passed (pending minor corrections). He died five weeks later. I learned on 6th August 2002 that the minor corrections to the thesis had been accepted. Ironically, that was the day of his funeral. I would like to dedicate this thesis to the memory of my dad who was always interested in how it was going.
STATEMENT REGARDING THE AUTHORS INVOLVEMENT IN THIS WORK

All the work in this thesis has been undertaken solely by Iain Beith, except the investigation into the reflex control of the ipsilateral and contralateral rectus abdominis muscles, including the use of vibration. This work was initially undertaken with Stelios Myriknas who then submitted this as project work, in partial fulfilment of the MSc in Neuroscience at University College London. The investigation of the reflex control between the RA muscles has subsequently been extended by me, Iain Beith.
GLOSSARY OF TERMS

RA – rectus abdominis
EO – external oblique
IO – internal oblique
TrA – transversus abdominis
IC – iliocostalis lumborum
LM – lumbar multifidus
ES – erector spinae
EMG – electromyography
ASIS – anterior superior iliac spine
PSIS – posterior superior iliac spine
NZ – neutral zone
EZ – elastic zone
Homologous – left and right pairs of trunk muscles i.e. left and right EO
i* – ipsilateral
cr* - contralateral
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1 INTRODUCTION.

1.1 Introduction to the study.

Stability of the lumbar spine is dependent on three factors; the connective tissue joining the adjacent vertebrae, the many muscles which overly these bones, and an intact central nervous system to control these muscles (Panjabi, 1992a). The motoneurone pools controlling the muscles of the lumbar spine are subject to many different inputs, both from spinally mediated reflex pathways, and from supraspinal sources. This thesis details an investigation into the reflex control, evoked from muscles afferents, of three abdominal and two paraspinal muscles, each of which is arranged differently relative to the lumbar vertebral column. In order to justify the experimental design utilised to investigate the reflex control of these muscles, evidence from different disciplines first needs to be introduced.

Initially, the anatomical arrangement of the lumbar vertebral column and the need for stability will be outlined. A description of the position, attachments, fibre orientation, and internal make up of the abdominal muscles studied will then be given. This includes the rectus abdominis (RA), external oblique (EO) and internal oblique (IO), plus transversus abdominis (TrA), which even though it was not studied directly, is relevant due to its attachments to IO. The function of these muscles will then be reviewed including their voluntary activation patterns and their responses to different perturbations investigated using electromyography (EMG). Two paraspinal muscles in the lumbar region, the iliocostalis lumborum (IC) and the lumbar multifidus (LM) were also studied, and their positions, attachments, fibre orientation, internal make up and function as revealed by EMG are also described. An overview of the stretch reflex and tendon jerk is then undertaken, with particular reference to the existence of
heteronymous reflex connections from group Ia muscle afferents from muscle spindles in one muscle, to those in synergistic muscles. In addition, pathways underlying spinally mediated reciprocal inhibition between muscles on opposite sides of a joint will also be outlined. Finally, an overview of longer latency reflex effects in response to tendon jerks will be described. Having highlighted the relevant evidence and identified the need to study the reflex connections between the abdominal muscles, the aims of the experiments undertaken are then summarised.

1.2 Stability of the lumbar spine.

The underlying focus for this study is that of lumbar spine stability and it is therefore necessary to define the term. Pope & Panjabi (1985) when referring to the lumbar spine defined instability as being “a loss of stiffness, where stiffness is the ratio of the load applied to a structure to the motion of the structure that results”. As the vertebral column is made up of many individual bones which articulate with each other, there is a need for appropriate levels of stiffness between these to maintain stability. The vertebral column is made up of 24 individual vertebrae in three regions, the cervical, the thoracic and the lumbar regions (figure 1.1). Each vertebrae articulates with the adjacent vertebrae rostral and caudal to it, via an intervening intervertebral disc and one synovial facet joint on each side. There are seven cervical vertebrae, 12 thoracic vertebrae, which also articulate with 12 ribs on each side making up the thoracic cage, and five lumbar vertebrae. In addition, there are fused vertebrae, which make up the sacrum and coccyx.
Figure 1.1. The human vertebral column, with the thoracic cage, muscles and supporting connective tissue removed. The three regions are arranged from top to bottom, seven cervical vertebrae, 12 thoracic vertebrae and five lumbar vertebrae with the sacrum and coccyx at the bottom. Adapted from Williams et al. (1989).
A typical lumbar vertebra is illustrated in figure 1.2. The main points to note are that, i) the vertebral canal houses the spinal cord and the cauda equina, ii) the kidney shaped surface which butts up against the intervertebral disc interposed between adjacent vertebrae and iii) the articular processes as indicated form the facet joints with the vertebrae above and below. A cross sectional view of the bones, joints and ligaments in situ in the sagittal plane is shown in figure 1.3. Although only two full segments are shown, viewed in conjunction with figure 1.1 the multisegmented system is obvious, as is the need for stability between all adjacent vertebrae. However, there are marked differences in the stability of the cervical, thoracic and lumbar regions.

Each cervical vertebra articulates with the adjacent vertebrae. These joints have a wide range of movement therefore allowing the head to be oriented in widely varying positions. However, the cervical spine is not usually subject to large loads as only the head needs to be supported. In contrast, the thoracic spine articulates not only between adjacent vertebrae, but also with the ribs on either side. This forms the thoracic cage, which increases the stability of the thoracic spine (Morris et al. 1961). The lumbar spine consists of lumbar vertebrae, which articulate with adjacent vertebrae, whilst supporting the head, neck, upper trunk and arms. This region is therefore subject to more loading than both the cervical and thoracic spines. The lumbar vertebrae are larger than those of both the cervical and thoracic spines to cater for the extra load. Whilst all these regions are supported by ligaments and joint capsules, it is now well established that the stability of the lumbar spine is also dependent on the muscles of the trunk (Lucas & Bresler 1960; Kaigle et al. 1995; Morris et al. 1961; Wilke et al. 1995).
Figure 1.2. A typical human lumbar vertebra. All the tissues normally attached have been removed. (Williams et al. 1989)

Figure 1.3. Cross-section through the human lumbar spine illustrating the joints between adjacent vertebrae and the connective tissue surrounding those joints. (Williams et al. 1989)
Panjabi (1992a) proposed a model of the spinal stability system which is shown in figure 1.4. This consists of the passive subsystem (bones and connective tissue) the active subsystem (the muscles) and the control subsystem (both peripheral and central nervous system components linked to the first two subsytems).

Panjabi also defined the neutral zone (NZ) and an elastic zone (EZ) of joint mobility (Panjabi, 1992b; Kumar & Panjabi, 1995). The NZ is defined as “that part of the range of physiological intervertebral motion measured from the neutral position within which the spinal motion is produced with minimal internal resistance”. This relates to the amount of slack in the surrounding tissues supporting the joint. The EZ is “that part of the physiological intervertebral motion measured from the end of the NZ up to the physiological limit. Within the EZ spinal motion is produced against a significant internal resistance”. Panjabi (1992b) proposes that the NZ is a better indicator of spinal instability than overall range of motion, and suggests that the muscles around a
joint contribute to maintenance of an appropriately small NZ. In addition, Panjabi (1992a) proposed that an increase in the neutral zone may contribute to the development and maintenance of low back pain.

1.3 Classifying trunk muscles by position.

Bergmark (1989) studied the stability of the lumbar spine from a mechanical engineering perspective, particularly the role of different trunk muscles. From this he devised a classification of the muscles dependent upon attachment, with those attaching directly to the vertebrae being termed local muscles, and those attaching between the thorax and pelvis being termed global muscles. From Bergmark's calculations of the distribution of forces affecting the lumbar spine, the global muscles are identified as being ideally positioned further from the axis of joint rotation to counteract external loads. The muscles of the local system, being closer to the vertebral column, are affected more by internal forces related to posture. Prior to outlining the role of the abdominal and paraspinal muscles there is a need to identify the position of these muscles, specifically their attachments, depth and fibre direction. This will initially be undertaken for the abdominal muscles, followed by the paraspinal muscles.

1.4 Abdominal muscle anatomy and function.

1.4.1 Rectus abdominis.

The RA muscle is situated on the anterior surface of the abdomen as illustrated in figure 1.5a, and is broader in the upper abdomen than the lower abdomen (Williams et al. 1989). It is attached proximally to the cartilages of the 5th, 6th and 7th ribs and in some individuals it is also attached to the ziphoid process. The fibres run downwards almost
vertically (Ng et al. 1998) attaching to the pelvis on the crest of the pubis and the ligaments covering the symphysis pubis. The left and right muscles both have three bands of connective tissue arranged horizontally which compartmentalise the muscle, and the lowest band is level with the umbilicus. These are the only muscles on the anterior aspect of the abdomen immediately either side of the midline and are, by Bergmark’s definition, global.

1.4.2 *External oblique.*

The EO muscle is positioned on the anterolateral aspect of the abdominal wall and is the most superficial of the three muscles that make up the abdominal wall (figure 1.5a). It attaches proximally via digitations to the external surface and lower borders of the eight lowest ribs. The posterior fibres run almost vertically downwards and attach into the outer lip of the iliac crest (Williams et al. 1989). The middle and anterior fibres which attach to the upper ribs are oriented downwards and forwards and attach via a central tendon in the midline (see below for details). Below the anterior superior iliac spine (ASIS) the EO tendon attaches to the inguinal ligament on the opposite side. The details of the attachments of the EO to the contralateral muscles and tendons, is given below.

1.4.3 *Internal oblique.*

The IO muscle also forms part of the anterolateral abdominal wall and is situated deep to the EO muscle (figure 1.5b). It is attached to the inguinal ligament below the ASIS, from the middle lip of the anterior two thirds of the iliac crest and part of the thoraco-lumbar fascia the lateral raphe (see figure 1.6), on the posterior aspect of the iliac crest (Williams et al. 1989). This allows the IO to exert some pull on the L3 to L5 vertebrae
Figure 1.5. The positions of the abdominal muscles. a) Rectus abdominis and external oblique, b) internal oblique and c) transversus abdominis. Taken from Williams et al. (1989)
via the attachment to the lower part of the thoraco-lumbar fascia (Bogduk & Macintosh, 1984; Bogduk, 1997). As can be seen in figure 1.5c, the muscle fibres extend in different directions from the different attachments, so that the upper and lower fibres diverge approximately 90°. The most posterior fibres extend from the iliac crest almost vertically upwards to attach to the ribs on the same side. The fibres from the anterior iliac crest are directed upwards and medially and pass behind and in front of the RA muscle (see below). Those from the anterior part of the iliac crest in the region of the ASIS are oriented horizontally, whilst the lowest fibres pass downward and medially and attach with the TrA muscle into the crest of the pubis. The attachments to the contralateral muscles via the central tendon, are detailed below.

1.4.4 Transversus abdominis.

The TrA muscle is the deepest of the muscles of the anterolateral abdominal wall being situated beneath IO and EO (figure 1.5c). It is attached to the inguinal ligament below, from the inner lip of the iliac crest, from the middle layer of the thoraco-lumbar fascia and from the inner surfaces of the lower six ribs (Williams et al. 1989). In contrast to the IO muscle, the fibres of TrA are oriented parallel to one another being horizontal throughout. Posteriorly, they are able to exert force on all the lumbar vertebrae (Bogduk & Macintosh, 1984). It is only in the midline anteriorly that the aponeurotic expansions diverge up and down, and these expansions form deep and superficial layers. The attachments to the contralateral muscles, via the central tendon are detailed below.
1.4.5 Attachment of the abdominal muscles posteriorly.

The EO muscle attaches proximally to the thoracic cage. In contrast the IO and TrA attach posteriorly to the thoraco-lumbar fascia, which in turn attaches to the lumbar spine (figure 1.6).

![Thoraco-lumbar fascia](image)

![Erector Spinae](image)

Figure 1.6. The thoraco-lumbar fascia. a) The position of the thoraco-lumbar fascia on the posterior aspect of the trunk (adapted from Williams et al. 1989) and b) the posterior attachment of the transversus abdominis (TrA) and internal oblique (IO) muscles to the vertebral column via the thoraco-lumbar fascia (adapted from Bogduk, 1997).
The TrA muscles attach to the lumbar spine from L1 to L5 via the middle layer of the thoraco-lumbar fascia (figure 1.6b). Both the TrA and IO muscles attach to the posterior layer of the thoraco-lumbar fascia which in the majority of subjects only attaches from L3 to L5 (figure 1.6b). The direction of pull of both muscles and the effect of this on the lumbar spine are also shown in figure 1.6b. In addition, both IO and TrA muscles attach to the inner rim of ilium.

1.4.6 Attachments of the anterolateral abdominal wall muscles anteriorly.

The EO, IO and TrA muscles of both sides attach anteriorly to the linea alba in the midline, however the nature of these attachments are intricate (Askar, 1977; Rizk, 1980, figure 1.7). Both EO and TrA muscles attach to their homologous counterpart contralaterally. However, the IO muscle does not attach to it’s homologous counterpart but divides into a superficial layer which attaches to the opposite EO, and a deep layer which attaches to the opposite TrA (figure 1.7). This is achieved by the tendons splitting to create individual slips of tendon which pass between the different layers. These slips interdigitate to allow a muscle from one layer to attach to those of a layer either deeper, or more superficial.

In the upper abdomen the EO and IO tendons pass anterior to the RA and the TrA, and IO muscles pass posterior to the RA (figure 1.7b). In contrast, in the lower abdomen all the tendons pass anterior to the RA (figure 1.7a). It is also important to note that level with the ASIS there are no EO muscle fibres only the EO tendon, (a point which will become apparent later in relation to surface EMG recordings from the IO muscle).
Figure 1.7. Illustration of the attachments between the anterolateral abdominal wall muscles. The upper and lower diagrams are cross sections through the anterior abdominal wall a) above the umbilicus and b) level with the anterior superior iliac spine. The muscles are illustrated by colour; the rectus abdominis muscles (RA, green), the transversus abdominis (black), the internal oblique (red) and the external oblique (blue) muscles. All tendons pass anterior to the RA in the lower abdomen and pass both in front of and behind the RA muscles in the upper abdomen. Data is taken from Askar (1977) and Rizk (1980).
Consequently, the IO muscle at this point is attached to both the pelvis on the opposite side via the contralateral TrA, and the thoracic cage via the contralateral EO.

### 1.4.7 Innervation of the abdominal muscles.

The abdominal muscles are supplied by the thoracic and upper lumbar nerves. The RA is supplied by the nerves from T6 to T12, the EO from T6 to T12 and the IO from T6 to L1 (Williams et al. 1989). Each of these thoracic nerves to both the RA (Duchateau et al. 1988; Hammond et al., 1995) and the EO (Schlenz et al. 1999; Kondo & Bishop, 1987) contain only nerve fibres from one segmental level. It is not known if the nerves from each segmental level supplying IO and TrA remain separate throughout their entire length, but there is no reason to suspect that they do not.

Both Coers (1959) and Voss (1971) have confirmed that muscle spindles exist within the abdominal muscles. Voss (1971) in a review of the relevant literature gives values for the density of spindles per gram of muscle for the majority of human muscles. The respective density of muscle spindles for the abdominal muscles are as follows; RA - 2.2%, EO - 3.5%, IO - 3.0%, TrA - 7.3%.

### 1.4.8 Location of the motoneurone pools of the abdominal muscles.

The motoneurone pools in the ventral horn of the thoracic spinal cord have been identified in the rat (Smith & Hollyday, 1983), the cat (Holstege et al. 1987; Miller, 1987; Tani et al. 1994) and the rhesus monkey (Sprague, 1951). However, the identity of the exact muscles related to each motoneurone pool has only been confirmed using staining techniques for the EO in the rat (Smith & Hollyday, 1983) and for RA, EO, IO and TrA in the cat (Holstege et al. 1987; Miller, 1987; Tani et al. 1994). Whilst there are some discrepancies between the rostral extent of the motoneurone pools related to
each muscle described in each study, a pattern is also obvious. The RA motoneurone pool is the most extensive ranging from the upper thoracic spinal cord to the upper lumbar cord. The EO motoneurone pool is consistently reported to extend from the mid-thoracic spinal cord to the upper lumbar spinal cord in the cat (Holstege et al. 1987; Miller, 1987; Tani et al. 1994) and probably in the rat (Smith & Hollyday, 1983). The IO muscle is the least extensive being situated in the lower thoracic and upper lumbar spinal cords spanning between three and four segments (Holstege et al. 1987; Miller, 1987; Tani et al. 1994). The TrA motoneurone pool position has only been reported by Holstege et al. (1987) and Miller (1987) and this extends from mid thoracic to upper lumbar spinal cord. Holstege et al. (1987) report the extent of the motoneurone pools to be more rostral in the spinal cord than either of the other studies. The levels reported above are those with which all authors agree. The position of each motoneurone pool within laminae IX of the ventral horn has also been described. The motoneurone pools of EO, IO and TrA are positioned laterally within the thoracic ventral horn. Only the RA muscle motoneurone pool is reported to be more medially situated than EO, IO and TrA.

1.4.9 Muscle fibre type of the abdominal muscles.

Three studies have investigated the fibre types that make up the abdominal muscles (Caix et al. 1984; Haggmark & Thorstensson, 1979; Johnson et al. 1973). Johnson et al. (1973) studied the RA in six cadavers and found varying values (31-56%) for the number of type I fibres relative to type II. Caix et al. (1984) recorded the relative number of type I fibres for all four muscles as; RA – 69%, EO – 52%, IO - 64% and TrA – 68%. However, these authors did not report the variability for each muscle or compare the mean values statistically. This is relevant because Haggmark & Thorstensson (1979) recorded no differences in the mean percentage values of type I
fibres in the four muscles. The percentage of type I fibres in each muscle were as follows; RA - 55%, EO - 58%, IO - 56% and TrA - 56%. Intriguingly, the variation in fibre type distribution between subjects was wide for RA, EO and IO but not for TrA. In fact, the TrA muscle was always composed of more than 50% type I fibres, but in three of 13 subjects type I fibres formed less than 50% of the overall number of fibres in RA, EO and IO. In summary however, the abdominal muscles have a high percentage of type I muscle fibres indicating that they are likely to have a role in maintaining posture, as their position within the trunk indicates.

1.5 The functions of the abdominal muscles.

The function of the abdominal muscles has been extensively investigated over the last 50 years, revealing involvement in such diverse functions as respiration, speech, all expulsive acts such as sneezing, coughing, and vomiting, movement and maintenance of posture (Iscoe, 1998). Initial studies identified the different movements associated with activity in certain muscles, which related well to the different fibre orientation of each muscle (figure 1.5, Carman et al. 1972, Floyd & Silver, 1950 among others). The RA muscles have therefore been shown to produce flexion (DeSousa & Furlani, 1974). The EO and IO on the same side produce side flexion to the same side and the EO and IO muscles on opposite sides are both active during axial rotation.

1.5.1 Co-activation of the left and right abdominal muscles.

Following on from these studies, Pope et al. (1986) recorded EMG activity in all four oblique muscles during axial rotation against resistance. They expected to see no EMG activity in the opposite EO/IO pair, which were not producing the movement, or in either RA muscle. Contrary to expectations, all four oblique muscles (left and right EO
and IO) were activated simultaneously at various torque levels up to maximum voluntary contraction, as were both RA muscles. Similarly both RA muscles predicted to be inactive during axial rotation showed EMG activity. In fact, there was no significant difference in the amplitude of the EMG activity in the left and right IO or RA muscles, even though the task was asymmetric.

Similar patterns of co-activation of all abdominal muscles on either side have since been repeated in many studies during different tasks (McGill, 1991; Peach et al. 1998; Thelen et al. 1995; Zetterberg et al. 1987; Huang et al. 2001). This has also lead to a number of authors modelling the co-activation patterns seen (Cholewicki et al. 1995; Gagnon et al. 2001; Gardner-Morse & Stokes, 1998; Marras & Granata, 1997). The conclusion drawn is that the co-activation observed, particularly in the oblique muscles, provides stability for the trunk, as well as producing movement of the vertebral column. The mechanism by which this occurs has been the subject of much conjecture (reviews by Bogduk, 1997 and Barker & Briggs, 1999). This increase in stability is likely to be produced via the attachments of both the middle and posterior bands of the thoracolumbar fascia directly on the vertebral column (Tesh et al. 1987; Bogduk & Macintosh, 1984). Whether this is achieved by the action of the TrA and IO directly on the vertebral column, or by an increase in intra abdominal pressure via co-activation of TrA (Huang et al., 2001) and IO muscle on both sides (Morris et al. 1961; Cresswell & Thorstensson, 1989), is still unclear.

1.5.2 Abdominal muscle activity in response to a perturbation.

Various studies have confirmed that the RA muscle responds to translation of the support surface whilst standing (Henry et al. 1998 & 2001; Horak & Nashner, 1986; Keshner et al. 1988). The earliest reported onset of the response to this perturbation
was 73ms after the platform was moved, but was more commonly 100ms or longer
(Horak & Nashner, 1986). Complementing these studies Zedka et al. (1998) also
reported activity in RA, EO and IO muscles on both sides to postural perturbations in
both sagittal and frontal planes, but no latencies of these responses are given. Radebold
et al. (2000 & 2001) positioned subjects in a semi seated position while resisting a load,
which forced the subjects into either flexion, extension or side bending. The load was
released and the reaction of both agonist and antagonist muscles to this change were
then observed. The latency of antagonist activity to counteract the sudden change in
loading in all directions was between 59 and 70ms, longer than is necessary for a
spinally mediated response in the appropriate muscles (Kondo et al. 1986; Kondo &
Bishop, 1987; Macefield & Gandevia, 1992, see below). Hodges et al. (2001) describe
a similar finding for responses in the TrA muscle, probably evoked by arm afferents
stimulated during a perturbation of bilateral arm movements, with a latency from the
perturbation of approximately 50ms.

Only one study reports the abdominal muscles responding to a perturbation at short
latency (Cresswell et al. 1994). Subjects wore a harness attached over the shoulders
with a pouch on both flexor and extensor aspects. A 5kg load was dropped in the pouch
either under the control of the subject, or at a time not under the subject’s control.

When subjects controlled the timing of the load being dropped, the abdominal muscles
were active before the perturbation. However, with the unexpected load the abdominal
muscle activity began after the perturbation, with latencies ranging from 24 to 33ms
after the load dropped. This is only slightly longer than spinally mediated reflex
latencies (Kondo et al. 1986; Kondo & Bishop, 1987; Macefield & Gandevia, 1992, see
below).
The preceding review highlights various aspects of abdominal muscle function, and in particular that the left and right abdominal muscles are commonly co-activated. Moreover the role of spinally mediated reflex pathways underlying these activation patterns is unknown. This synergy of contralaterally positioned muscles may be supported by reflex connections from muscle afferents in one muscle to the others and the evidence supporting the existence of such connections is reviewed in section 1.7.

1.6 Paraspinal muscle anatomy and function.

The paraspinal muscles chosen for the present study are the iliocostalis lumborum (IC) and lumbar multifidus (LM) muscles due to the contrasting nature of their attachments. The IC muscle attaches to the thorax and the pelvis and is therefore, according to Bergmark's classification (1989) described as global, whereas the LM attaches directly to the vertebral column and the sacrum and is according to Bergmark's classification described as local.

1.6.1 Iliocostalis lumborum.

The IC attaches from the posterior aspect of the lower ribs to the posterior aspect of the iliac crest. The fibres are oriented downwards and slightly medially (figure 1.8). Being positioned more laterally than the LM a greater mechanical advantage is achieved. This provides for better control of spinal movements in the frontal plane.

1.6.2 Lumbar multifidus.

The LM is a multisegmented muscle arising from the spinous processes of all the lumbar vertebrae (L1 – L5). The muscle fibres attaching to each vertebrae radiate downwards and laterally to attach to one of the following bones; any of the more distal
vertebrae, the posterior superior iliac spine (PSIS), or the sacrum (Macintosh et al. 1986, Bogduk, 1997, figure 1.8).

Figure 1.8. Muscles of the extensor aspect of the trunk. The superficial layers of muscle and fascia have been stripped away and both muscles studied, the lumbar multifidus (LM) and iliocostalis lumborum (IC) are revealed being circled and labelled appropriately. Adapted from Williams et al., (1989)
The fibres attaching from each vertebra are separated into several slips arranged from superficial to deep, with the superficial fibres spanning more segments than the fibres situated deeper. The deepest fibres attach to the adjacent vertebrae and are therefore unisegmental. The most superficial fibres span many segments, up to a maximum of five from L1 to the posterior superior iliac spine (PSIS) and are therefore multisegmental.

1.6.3 Innervation of the IC and LM muscles.

The innervation of the LM has been described by Macintosh et al. (1986) and Shindo (1995) as being segmental. Hence the muscle fibres which attach proximally to each individual vertebra are innervated by the dorsal rami of the nerve root exiting the vertebral column at the level of that vertebra. The IC muscle is innervated by the lateral branch of the dorsal rami of L1 to L4 nerve roots. The L1 branch enters the muscle at its most rostral, and the branch from L4 at its most caudal. However the non-segmental attachments of the IC muscle mean it is unclear which nerve root supplies exactly which part of the muscle.

Voss (1971) and Amonoo-Kuofi (1982 & 1983) have confirmed the presence of muscle spindles in the IC muscle, and Amonoo-Kuofi (1982 & 1983) and Nitz & Peck (1986) have confirmed that muscle spindles are situated in the LM. However, direct comparisons of the relative densities of the spindles in these different muscles are hampered by the different methods used to calculate the densities in each study. Voss (1971) used muscle spindles per gram weight of muscle, Amonoo-Kuofi (1983) used the number of muscle spindle per cross sectional area of the muscle and Nitz & Peck (1986) expressed the density as the number of muscle spindles relative to the number of extrafusal muscle fibres. In addition, comparisons within each study have not revealed
differences between the density of muscle spindles in the IC and LM muscles. However, Amonoo-Kuofi (1983) did identify the greatest density of muscle spindles to be within the iliocostalis muscle in the thoracic spine. As this is an extension of the IC in the lumbar spine this may be of relevance to the present study where comparisons of the reflex activity in IC and LM are to be made. However, the most important factor is confirmation that muscle spindles do exist within the IC and LM muscles.

1.6.4 Location of the motoneurone pools of the paraspinal muscles.

The only report of the position of the IC motoneurone pool is in the rat (Smith & Hollyday, 1983) and this only describes the position in the ventral horn and not the segmental levels they extend across. The motoneurones were found to be clustered in the most ventral part of the ventral horn. The position of the LM motoneurone pool has been described in the cat by Vanderhorst & Holstege (1997). These were situated in the medial part of the ventral horn and were found to be confined to specific levels suggesting they may not form a continuous column spanning different segments. However, these authors acknowledge that not all of the LM muscle was exposed to the stain applied and this may account for the separately identified motoneurone pools at different levels. Whilst comparison between these two studies suggests the LM muscle has motoneurone pools situated nearer to the midline than the IC, these studies were in different species and therefore the comparison is not conclusive.

1.6.5 Fibre typing of the paraspinal muscles.

All the studies of fibre type distribution in the lumbar paraspinal muscles report more than 50% type I fibres (Sirca & Kostevc, 1985; Thorstensson & Carlson, 1987; Jorgensen et al. 1993; Zhao et al. 2000). In the LM muscle the proportion of type I
muscle fibres relative to type II muscle fibres has been reported by Thorstensson & Carlson (1987) as 62%, and by Zhao et al. (2000) as 58% in the LM muscle on the asymptomatic side of subjects with unilateral disc protrusion. Jorgensen et al. (1993) also report type I fibres as constituting 51% of the fibres present in the superficial LM, and 57% of the fibres in the deep LM. In addition, these authors (Jorgensen et al. 1993) report the distribution of type I fibres in the IC muscle in cadaveric specimens, as being 58% in the deep part of the muscle, and 52% in the superficial part. These authors are therefore the only group to directly compare the proportions of fibre types in IC and LM, and this comparison reveals no difference between the two muscles. As for the abdominal muscles, the variation in distribution in the IC and LM muscles between subjects is wide. In conclusion, no obvious difference in the distribution of type I and type II fibres, in IC and LM has been demonstrated, as is the case for the abdominal muscles (RA, EO and IO).

1.6.6 Functions of the paraspinal muscles.

Lucas & Bresler (1960) identified the importance of the paraspinal muscles in contributing to lumbar spine stability by removing these muscles from cadaveric specimens and identifying the compressive load required to compromise the stability of the spine as 80N. Crisco & Panjabi (1991) also modelled the relative effectiveness of paraspinal muscle fibres attaching to the vertebrae and found those spanning more segments and being more laterally positioned contribute more to stability. However, no biomechanical studies comparing the ability of the LM and IC muscles to stabilise the lumbar spine have been carried out.

Differences in function between the IC and LM muscles have also been demonstrated using both fine wire electrodes (Jonsson, 1970; Morris et al. 1962; Pauly, 1966; Huang...
et al. 2001) and surface electrodes (Peach et al. 1998; Arendt-Nielsen et al. 1995; Dofferhof & Vink, 1985; Vink et al. 1987; Vink & Karssmeijer, 1988). The EMG activity within different muscles during various tasks were compared, and whilst absolute measures of EMG were not always recorded, a contrasting pattern of activity of these two muscles has emerged.

Joseph & McColl (1961) have reported minimal activity in the lumbar paraspinal muscles during upright standing. In sagittal plane movements, the IC and LM muscles on both sides are active during forward flexion (Bogduk, 1997). However, Pauly (1966) reports that LM appears to be more active than IC, whilst both IC and LM are more active on return from full flexion to extension. Leaning back in standing produces more activity in IC than LM (Morris et al. 1962), whereas extending against gravity in prone lying activates both muscles but LM more than IC (Pauly, 1966). During tasks in the frontal plane, EMG activity in IC and LM is limited to the one side best positioned to resist the load applied (Huang et al. 2001; Jonsson, 1970). It is also worthy of note that this activity was not always seen in standing as highlighted above (Joseph & McColl, 1961) but was apparent when leaning forward (Morris et al. 1962). During axial rotation the most complex pattern of activation between the two muscles is reported by Peach et al. (1998). Rotation towards one side is produced by the IC on that side whilst rotation back from that position is produced by the LM on the same side. Therefore, in this instance the ipsilateral IC (iIC) and ipsilateral LM (iLM) muscles are antagonistic to one another. This also means that during axial rotation the left and right IC muscles are antagonistic to one another, as are the left and right LM muscles. One further study of note comparing EMG activity in LM and IC shows different recruitment of the two muscles (Vink et al. 1987). LM activity increases linearly up to maximum voluntary contraction (MVC), whereas IC recruits non-linearly and generates
more power. These authors infer from this data a postural role for the LM and that of force generator in the frontal plane for IC.

In addition, the role of the paravertebral muscles on either side during gait has also been studied in both cat (Carlson et al. 1979) and man (Carlson et al. 1988; Arendt-Nielsen et al. 1995; Dofferhof & Vink, 1985; Vink et al. 1989). All these studies demonstrated bilateral co-activation of paraspinal muscles during gait which coincided with the beginning of weight bearing (heel strike in man) in each limb. Macpherson & Fung (1998) Wada et al. (1999) and Wada & Kanda (2001) also suggest that the role of the paraspinal muscles is to increase the stiffness of the lumbar spine.

In summary, the activation patterns of IC and LM muscles are more complex and variable than those of the abdominal muscles. The muscles can work either synergistically or antagonistically depending on the task. These different activation patterns could not therefore be used to predict whether reflex control of these muscles is by excitatory or inhibitory reflexes or no reflex connections at all. Indeed the more complex organisation of these muscles may require supraspinal control.

1.6.7 Responses of the paraspinal muscles to perturbations.

Various studies have demonstrated responses in the paraspinal muscles in response to perturbations. Co-activation of the paraspinal muscles on both sides occurs when a subject stands on their toes, so reducing the size of the base of support (Pauly, 1966). It may be that this position is the most likely to evoke responses in these muscles due to the small base of support, creating more demand for postural muscle activity. Zedka et al. (1998) studied EMG activity in the erector spinae muscle in sitting subjects. The subjects arm was placed on a table, and both active and passive movements of the wrist
were performed. The EMG activity was found to be in phase with the wrist movements performed, and therefore these muscles were probably responding to the perturbation through the arm to the trunk, evoking homonymous reflex responses in ES. Zedka et al. (1998) studied seated subjects with legs outstretched and perturbed the support surface in either sagittal or frontal planes. This revealed contrasting activation patterns of the paraspinal and abdominal muscles in the frontal plane. Whilst the abdominal muscles on both sides were active simultaneously, the left and right paraspinal muscles responded alternately in a reciprocal manner. These studies demonstrate that the paraspinal muscles do respond to perturbations and suggest that those on either side respond differently whereas the abdominal muscles on either side respond similarly.

In other studies responses have not only been observed in the paraspinal muscles, but the latencies of these responses have also been measured. Activity in the paraspinal muscles in response to a perturbation of the supporting surface whilst subjects are standing, occurs at the same latency as that evoked in the abdominal muscles (Henry et al. 1998 & 2001; Horak & Nashner, 1986; Keshner et al. 1988). However, as for the abdominal muscles, these responses are longer than would be required for short latency spinally mediated effects, never being shorter than 100ms after the perturbation. Radebold et al. (2000 & 2001) observed the responses of all trunk muscles to the release of a load on one side of the trunk being held by the trunk muscles. The responses in the paraspinal muscles were between 50 and 70ms, i.e. similar to that in the abdominal muscles. A similar study in the sagittal plane by Fallentin et al. (2001) showed responses of a similar or longer onset latency (range 50-90ms) in the paraspinal muscles.
As for responses observed in the abdominal muscles, only Cresswell et al. (1994) observed short latency responses in the paraspinal muscle to unexpected loading. The activation patterns of the paraspinal muscles on either side in response to a perturbation show task dependency with both co-activation (sagittal plane) and reciprocal activity (frontal plane), similar to the activation patterns during voluntary activity.

1.7 Abdominal and paraspinal muscle co-activity.
Zetterberg et al. (1987) reported the unexpected finding of activity in the abdominal muscles during volitional activity of the extensor muscles, but not in the paraspinal muscles during voluntary activity in the abdominal muscles. Cholewicki et al. (1997) identified co-activation of flexor and extensor muscles during repeated flexion and extension particularly around the neutral position when changing from flexion to extension. However, other authors have not identified such co-activity during volitional activation (Peach et al. 1998). Henry et al. (1998 & 2001) and Horak & Nashner, (1986) showed reciprocal activity between abdominal and paraspinal muscles during perturbations in the sagittal plane. Only Zedka et al. (1998) report possible co-activation of these two muscle groups during slow perturbations in the sagittal plane but not during faster disturbances. It is not known whether reflex pathways exist which facilitate the patterns of co-activation or reciprocal activity between flexor and extensor groups.

1.8 Short latency reflexes from muscle afferents.
Liddell & Sherrington (1924 & 1925) observed that stretching a muscle produces a reflex response within the same muscle. They confirmed the underlying mechanism as a reflex pathway via the spinal cord, and gave this response the term myotatic reflex.
The response was subsequently identified as being a monosynaptic two neuron reflex arc by Lloyd in the cat (1943a, 1943b), and by Magladery et al. in man (1951). The afferent fibres thought to be primarily responsible for this response are the low threshold Ia afferent fibres (Magladery & McDougall, 1950). These fibres originate from annulospiral endings within the muscle spindles. These intrafusal muscle fibres are sensitive to increases not only to a change in length (Granit, 1950), but also to the velocity of that change (Matthews, 1972). The effect of this short latency reflex is thought to be an increase in the stiffness of the underlying joint (Gielen et al. 1988; Vincken et al. 1983; Houk, 1976).

One way of evoking this reflex is via a mechanical tap, which stretches the muscle tendon complex, and the response to this stretch is often termed a tendon jerk. This stretch evokes activity within muscle spindles and the Ia afferent fibres innervating them. Burke et al. (1983) have demonstrated in man that stretch reflexes evoked in such a manner may also involve activity from both group II muscle afferents and probably cutaneous afferents, as well as Ia afferents. There is no specific evidence detailing the relative contribution of the different afferents, however it seems likely that Ia afferent activity is predominant. In addition, the reflex responses to a tendon tap are both monosynaptic and oligosynaptic (Burke et al., 1984). Eccles et al. (1957) and Eccles & Lundberg (1958) identified a widespread distribution of Ia muscle afferent fibres showing a complex pattern of connectivity particularly in the muscles at the hip and knee in the cat. This work has now been extended to studies in man using both electrical stimuli (Meunier et al. 1993; Pierrot-Deseilligny et al. 1981) and tendon jerks (McClelland et al. 2001; Miller et al. 2001; O'Sullivan et al. 1991).
Thus the stretch reflex is accepted as increasing stiffness of the underlying joints and the afferent fibres evoking this reflex often evoke responses in synergistic muscles. The abdominal muscles on both sides act in unison to increase the stiffness around the lumbar spine. Heteronymous Ia afferent connections between these abdominal muscles on both sides may therefore exist. An investigation of the possible reflex connections between the abdominal muscles by tapping on these muscles and recording the resultant reflex activity forms the basis of part of this thesis.

The activation patterns of the paraspinal muscles on either side of the spine are in contrast to the abdominal muscles more variable as described in section 1.6. Simultaneous excitation or reciprocal activity are observed in the same muscles during different tasks. Therefore hypotheses regarding the nature of any reflex connections between these muscles are less easy to formulate. There may be short latency heteronymous Ia afferent excitatory reflexes, particularly between the left and right LM as these muscles are thought to stabilise the vertebral column. However muscles positioned either side of a joint often exhibit inhibitory reflex connections. Such effects are likely to be mediated via at least a disynaptic pathway involving inhibitory interneurones. These interneurones have been extensively studied, primarily in those muscles which act as agonist and antagonist over the same joint in the limbs (for reviews see Baldissera et al. 1981; Jankowska 1992 and Schomburg 1990). The IC muscles, which are more laterally positioned than the LM, may be more analogous to this agonist antagonist relationship found in the limbs. Such inhibitory reflexes may therefore exist between these muscles on opposite sides.

Curtis et al. (1958) Edisen (1967) and Frank and Sprague (1959) have all identified crossed inhibitory effects in the sacral spinal cord of the cat. Whilst Jankowska et al.
(1978) identified crossed disynaptic inhibition between muscles on opposite sides of the
cat tail, Anderson (1977) and Rapoport (1979) did not identify crossed inhibition or
excitation between muscles on either side of the cervical spine. These contrasts are
likely to reflect the different functions of the tail and the neck muscles on either side of
the body. That the LM muscle attaches to either side of the vertebral column and IC
does not suggests differences in their functions and this may therefore be reflected in
different reflexes between these two muscles on either side of the lumbar spine.

1.8.1 Short latency excitatory crossed reflexes.

The existence of crossed reflex pathways is evident from both morphological and
electrophysiological studies. That afferent activity crosses the spinal cord to affect
motoneurones positioned contralaterally has long been established (Harrison &
Zytnicki, 1984; Harrison et al. 1986; Perl, 1959). In addition possible crossed
excitatory monosynaptic effects have been identified by Curtis et al. (1958) and Frank
and Sprague (1959), although these effects were not frequently seen. Morphological
studies support the existence of crossed monosynaptic connections. Primary afferents
have been observed to cross the spinal cord and terminate in the contralateral laminae
VIII and laminae IX (Matsushita & Tanami, 1983; Ritz et al. 1991; Edisen, 1967;
Scheibel & Scheibel, 1969). The dendrites of motoneurones within the ventral horn
have also been observed to extend across the midline of the spinal cord (Peterson, 1989;
Frank & Sprague, 1959; Scheibel & Scheibel, 1973; Jankowska et al. 1978; Rose &
Richmond, 1981; Ritz et al. 1992) and this may allow direct connections between
afferents on one side of the spinal cord, and motoneurones on the opposite side.
1.9 Reflexes in trunk muscles.

Whilst details of the distribution of heteronymous muscle afferent connectivity between trunk muscles is sparse, homonymous reflex responses in some abdominal and paraspinal muscles have however been studied. These will now be detailed.

1.9.1 Short latency reflexes in the abdominal muscles.

The reflex control of the abdominal muscles in response to electrical stimuli has been investigated by Hagbarth & Kugelberg (1958) and Kugelberg & Hagbarth (1958). This revealed some limited short latency reflex activity in muscles close to the stimulus originating from low threshold afferents. Longer latency reflexes from higher threshold afferents were also evoked and were more widespread throughout the whole trunk musculature. The muscles directly under the stimulus were facilitated whilst those on the opposite aspect of the trunk were inhibited. The latter reflex responses were identified by Kugelberg & Hagbarth (1958) as being evoked via cutaneous and nociceptive afferents and interpreted as providing protection for the underlying abdominal contents. The effect of muscle afferents on abdominal muscles has been investigated by Kondo et al. (1986) who used a tap on the abdominal wall to evoke a short latency response in EO and IO, whilst Macefield & Gandevia (1992) used the same technique to evoke a response in EO only. The responses evoked from tapping were of short latency and the authors concluded that at least the early part of the response was monosynaptic. Kondo & Bishop (1987) also evoked short latency responses in the EO muscle by electrically stimulating the intercostal nerve supplying the muscle. They concluded that these effects were primarily from muscle afferents. However, no studies of the heteronymous reflex connections between the abdominal
muscles have been undertaken but the activation patterns of these muscles highlighted suggest that reflex connections exist.

1.9.2 Short latency reflexes in the paraspinal muscles.

Tani et al. (1997) and Trontelj et al. (1979) evoked reflex activity in the paraspinal muscles on both sides by tapping in between the spinous processes of the vertebral column. However, it is uncertain which afferents are responsible for evoking these responses and these may include either joint and/or muscle afferents. Dimitrijevic et al. (1980) and Zedka et al., (1999) applied mechanical taps directly to the erector spinae on one side to investigate reflexes in the paraspinal muscles both ipsilateral and contralateral to the tap. Tapping at this point would preferentially evoke activity in the muscle immediately under the tapper. Dimitrijevic et al. (1980) reported short latency excitatory effects in the contralateral ES and interpreted this as being evoked by the perturbation from the tap ipsilaterally spreading to evoke activity in the contralateral muscle afferents so evoking a homonymous response. In addition, these authors identified a reduction in activity contralaterally on non rectified records and interpreted this as a silent period after the short latency excitation. However Zedka et al. (1999) did not report a short latency excitation contralaterally and when rectifying the data identified a short latency inhibition. The latency of this inhibition was on average 7ms longer than the ipsilateral excitation, i.e. longer than required for a delay due to a disynaptic pathway. This crossed inhibition is complimented by the studies identifying activity in the paraspinal muscles on one side only during lateral loading (Huang et al. 2001) and reciprocal activity in left and right sides (Zedka et al. 1998).
1.10 Long latency reflexes.

One further common effect observed in response to a mechanical tap, is a longer latency response after the short latency excitation. This was first observed by Hammond (1960) although it was Phillips (1969) who highlighted a possible transcortical route for the response and this hypothesis provoked many subsequent investigations (reviewed by Matthews, 1991). The debate as to the origin of the response has continued since with some authors favouring the transcortical route (Wiesendanger et al. 1975; Marsden et al. 1973), whilst others have identified the role of the slower conducting group II muscle afferents from muscle spindles (Anderson, 1977; Matthews, 1989; Schieppati & Nardone, 1997). The role of cutaneous afferents has been highlighted by others (Corden et al. 2000; Darton et al. 1985). It has been suggested more recently that the response may be mediated by different groups of afferents in distal and proximal muscles in upper and lower limbs (Thilmann et al. 1991) and in the same muscle during different tasks (Macefield et al. 1996).

One further piece of evidence worthy of note is reported by Gielen et al. (1988). These authors, when pronating the forearm, identified not only the expected short and long latency responses in the biceps muscle, but also long latency excitatory responses in the triceps muscle, which had not been stretched. Such simultaneous activation of both biceps and triceps at long latency was interpreted as a co-ordinated response in both muscles to stabilise the elbow. As the trunk muscles are thought to stabilise the trunk, it may be that a similar widespread long latency reflexes will be observed within the trunk muscles in response to stretch.
1.11 Summary and Predictions.

The evidence regarding the control of the abdominal and paraspinal muscles is incomplete. On the basis of the current knowledge the following predictions will form the basis of the investigation.

1. Short latency excitatory reflexes evoked from RA, EO and IO muscle afferents are expected to be apparent in RA, EO and IO muscles on both sides. These effects are predicted to be most potent between the muscles connected anatomically across the anterior abdomen (iEO to crEO, iEO to crIO and iIO to crEO).

2. Of the paraspinal muscles the ipsilateral IC and LM most often work synergistically. Therefore short latency excitatory reflexes between the ipsilateral IC and LM muscles are expected to be apparent. The nature and existence of reflexes between the IC and LM muscles on either side of the spine are less predictable. The reflex control of IC and LM muscles may also differ due to their different anatomical arrangement.

3. It is unclear from the available evidence whether short latency reflex pathways exist between the IO and LM muscles. Therefore, whether they do or do not exist needs to be confirmed.

4. As longer latency responses have been observed in the trunk muscles when perturbing the trunk, these may also be evoked when tapping the trunk muscles.
2 METHODS.

Possible reflex connections between the abdominal and paraspinal muscles were investigated in 24 subjects. The abdominal muscles investigated were RA, EO and IO muscles, whilst the paraspinal muscles investigated were the IC and LM. Subjects were excluded if they had any movement or neurological disorders, or current low back pain. All procedures were approved by the local research ethics committee of Kings College London and informed written consent was obtained from each subject.

2.1 Application of a mechanical tap to evoke reflex activity.

Reflex activity was induced by means of a mechanical tap produced by a tapping device consisting of a drive unit with a rounded polyethylene cap as a probe, to either the muscle belly or tendon of each of the muscles as shown in figures 2.1 & 2.2. The amplitude of the tap was 1.9mm, and the time to peak amplitude was no more than 1.9ms (this time is dependent on the load resisting the displacement of the tapper). Therefore the speed of the tap applied was approximately 1m/s. All experiments were undertaken by the same investigator holding the tapper in situ whilst subjects were standing. The responses were monitored during the experiments and adjustments made to the angle and/or pressure being applied to ensure that homonymous reflexes were evoked. When recording from the RA muscles, subjects were sometimes asked to lean back, to raise the level of background EMG. In contrast, when recording from the paraspinal muscles the subjects were usually asked to lean forward to raise the level of background EMG.
2.2 EMG recording.

The reflex responses were detected via self adhesive surface electrodes (Medicotest blue sensor), positioned with the poles 2cm apart as suggested by Fuglevand et al., (1992) and others. For the abdominal muscles, the electrodes were positioned on the skin over the left and right RA muscle bellies, the left and right EO muscle bellies, and the left and right IO muscles medial to left and right anterior superior iliac spines (ASIS, Ng et al. 1998, figure 2.1).

![Illustration of the points tapped and recorded from in relation to the anterior abdominal muscles. The points at which the taps were applied to induce a tendon jerk are indicated by crosses, and the position of the surface electrodes to detect EMG by pairs of black circles. Taps were applied at the upper cross over the rectus abdominis (RA) muscle belly, the most lateral cross over the external oblique (EO) muscle belly, and the lower cross on the internal oblique (IO) muscle, in order to induce a short latency homonymous stretch reflex in each muscle respectively. The upper pair of electrodes are positioned to detect EMG activity in the RA muscle, the most lateral pair over the EO muscle and the lowest pair over the IO muscle. For ease of presentation the points tapped and the electrodes are positioned on one side only but for all experiments both sides were tapped and recorded from.](image)
For the paraspinal group the electrodes were positioned over the IC and LM muscles and in line with the orientation of the muscle fibres (De Foa et al. 1989, figure 2.2).

Figure 2.2. Illustration of the points tapped on, and recorded from the paraspinal muscles. The points at which the taps were applied are indicated by crosses, and the position of the surface electrodes to detect EMG by pairs of black circles. Taps were applied at the lateral cross to stretch the iliocostalis lumborum muscle (IC), and at the cross near the midline to stretch the lumbar multifidus muscle (LM). The laterally placed electrode detects activity from IC and those nearer the midline to detect activity from LM. For ease of presentation the points tapped and the electrodes are positioned on one side only, but for all experiments both sides were tapped and recorded from.
2.3 Data collection.

For all protocols each sweep of data and the tapper were triggered via a 1 or 2ms square wave digital pulse, generated from Signal software version 1.9 or 2 (Cambridge electronic Design, (CED)). The electromechanical delay from this stimulus to the onset of the tap was less than 0.1ms. The data was sampled at 10kHz, pre-amplified (NL824), isolated and amplified (NL820), (overall gain 2000), band pass filtered between 30 – 3kHz (NL125), passed through an oscilloscope for visual inspection, converted into digital format via an analog to digital converter (1401 Micro, CED), processed in Signal (version 1.9 or 2 (CED)), and stored on computer for off line analysis. The EMG activity was collected for a period of either 200 or 250ms, with 50ms of data usually being collected before the stimulus and 200ms of data after the stimulus.

2.4 Experimental protocol.

Taps were applied at six points on the abdomen; i) on the left and right RA muscles, ii) on the left and right EO muscle bellies just distal to the attachment to the lower ribs in the mid axillary line, and iii) immediately medial and slightly superior to the left and right anterior superior iliac spines (ASIS) on the IO, as shown in figure 2.1. Experiments involving the RA muscle were undertaken with subjects in both standing, and leaning back, because a homonymous RA reflex could not always be evoked in RA in standing, whereas when leaning back a response was always seen. This was in contrast to the effect of leaning back on the reflex activity evoked when tapping on EO and IO. When leaning back and tapping on EO the amplitude of the responses evoked were smaller than in standing. When leaning back and tapping IO the amplitude of the responses were smaller and the reflexes were observed less frequently than in standing. It may be that leaning back increases the tension within both EO and IO, so that taps
applied in this position could not produce such a large displacement of the muscle, so reducing the amplitude of the stimulus to the receptors within each muscle. Due to the effect of leaning back relative to standing, the results when tapping the RA muscles are reported in both standing and leaning back, whereas those responses evoked when tapping over EO and IO are reported in standing only.

Taps were also applied at four points on the lumbar extensor muscles; i) on the left and right LM muscles at the proximal end of the muscle belly and ii) on the left and right IC muscles midway along the muscle belly as shown in figure 2.2. Each tap was repeated 30 times for each experiment, unless otherwise stated. Experiments were also undertaken to investigate any reflex connections between the IO and LM muscles. The protocol of the investigation of reflex activity between IO and LM differ in some aspects from that outlined so far. The details of these variations are given in chapter 8.

2.5 The application of vibration and its effect on short latency reflexes.

The effect of vibration on reflexes has been observed to reduce the amplitude of monosynaptic reflexes (Barnes & Pompeiano, 1970). One mechanism which may produce this effect is presynaptic inhibition evoked by Ia afferents on other Ia afferents (Desmedt, 1983; Stein, 1995). Therefore, whilst the taps were being applied to the iRA and iIO, these same muscles were simultaneously vibrated to investigate this phenomenon in the crRA and crIO muscles respectively. Vibration was applied by an electromagnetic vibrating device (Novasonic apparatus, Novafon) at a frequency of 50Hz.
2.6 Selecting the interstimulus interval.

Van Boxtel (1986) has reported that decreasing the interval between tendon jerks produces a small reduction in reflex amplitude. In order to identify the optimum interstimulus interval for the current study, 30 taps were applied to the IO muscle at intervals of 1, 2, & 5 seconds. The 30 traces were averaged and the latencies and amplitudes of the non-rectified reflexes compared for the different interstimulus intervals in both the iIO and crIO in 7 subjects. The amplitudes and latencies of these reflexes were compared using one way ANOVA. There was no significant difference between the latency (ipsilateral muscle p=0.95, crossed muscle p=0.72) or amplitude (ipsilateral muscle p=0.95, crossed muscle p=0.89) when tapping at different interstimulus intervals. This was repeated using the LM muscle homonymous reflex in 7 muscles in 5 subjects. Once again no significant difference was found for amplitude (p=0.50) or latency (p=0.83). The subsequent experiments were therefore undertaken at either 1 or 2 seconds interstimulus interval to reduce the time taken to complete the protocol.

2.7 Presentation of results.

The results of the investigation into each reflex are presented as follows; i) frequency of occurrence of the reflex as a percentage of the experiments undertaken, ii) the relative amplitude of the observed reflexes and iii) the latencies of the observed reflexes. Where appropriate, all the data are presented as mean ± standard error of the mean (SEM). 18 different reflex connections have been studied between the abdominal muscles, eight between the paraspinal muscles and a possible six between the IO and LM muscles. The reflexes reported in this study are defined as short latency (less than 27ms latency) and long latency (more than 38ms). This is because no reflexes occurred at latencies
between 27ms and 38ms. The short latency reflexes are reported before the long latency responses. Due to the large number of reflexes between the abdominal muscles, these results are reported in two different Results chapters. In chapter 4 reflexes between the EO and IO muscles are reported, whereas those involving the RA muscle are reported in chapter 5. Comparison of all these reflexes between RA, EO and IO is undertaken in chapter 6. The reflexes between the IC and LM muscles are reported and analysed in chapter 7. The results of the investigation into the short latency reflexes between the IO and LM muscles are reported in chapter 8. All the short latency reflexes in the abdominal and the paraspinal muscles are then discussed in chapter 9. A further investigation into possible asymmetry in the amplitude of the reflexes between the left and right internal oblique muscles is undertaken in chapter 10. The longer latency reflexes between all muscle groups are reported and analysed in chapter 11, and these are discussed in chapter 12. Chapter 13 includes a final discussion of all the results, and the conclusions of the study.

One further point of note regards the effectiveness of each reflex. Both the amplitude of the reflexes and the frequency with which they occur, are measures of the effectiveness of a particular group of afferents in evoking a reflex. Whilst both of these are detailed in the results section, a more useful way of describing the overall effectiveness of a particular group of afferents is if the two measures are combined. This has been achieved here by including in the measures of amplitude, those occasions in which no response was apparent, as zero amplitude. The resulting index is referred to as “potency”, and it is this measure that is used for the statistical analysis of the results.
3 METHODOLOGICAL CONSIDERATIONS.

3.1 Analysis of reflex activity.

The comparison of the reflexes in different muscles poses various technical difficulties, which will be outlined below. In summary, both non-rectified averaged, and average of rectified data were used, but for different purposes.

3.1.1 Identification of the presence of a reflex.

An excitatory reflex was included as being present if the reflex was obvious in the rectified traces. The majority of excitatory reflexes were also obvious in the non-rectified traces, however this was not the case for all reflexes and this point is discussed further below. The criteria used for inclusion when identifying a reflex on the non-rectified trace, was that at least one phase of a reflex waveform must be obvious. On the average of the rectified data an excitatory reflex was accepted as being present if the level of EMG activity rose above two standard deviations (2SD) from the background EMG activity (Wohlert, 1996; Wood & Smith, 1992). In contrast to the identification of excitatory responses, inhibitory responses could not be identified on non-rectified records. A response was accepted as being inhibitory, if on the rectified trace the level of EMG activity was reduced by more than 2SD of the mean background EMG prior to the stimulus being applied (Wood & Smith, 1992; Wohlert, 1996). The length of these inhibitory responses was also considered when identifying whether they were present. Wohlert (1996) used 8ms as an arbitrary lower time span for reflexes in lip muscles. For the present study, observation of all the inhibitory reflexes resulted in the decision to accept as a reflex a reduction in background EMG activity of 5ms duration or more.
3.1.2 Detection of small reflexes using rectified and non-rectified recordings.

Some reflexes, which seemed to be apparent on the non-rectified average, were not obvious and/or, deviated less than 2SD from the background EMG level on the averaged of the rectified data. These were not included as reflex responses, and three examples of this are shown in figure 3.1.

![Figure 3.1](image)

Figure 3.1. Examples of apparent short latency heteronymous excitatory reflex responses on non-rectified averages, which are not apparent on the average of rectified data. The first two traces are both in the contralateral iliocostalis lumborum (crIC) when tapping the ipsilateral IC and the third example is in the contralateral external oblique (crEO) on tapping the ipsilateral EO muscle. The first dashed line on each trace is the point at which the tap is applied and the second is the identified onset latency from each non-rectified trace respectively.
One further contrast between averages of rectified and non-rectified data was also noted in a small number of experiments when attempting to identify whether a reflex was present. This is illustrated in figure 3.2. The reflexes, which are small or non-existent on non-rectified average traces, are in these instances obviously present in the average of rectified data.

Figure 3.2. Excitatory reflex responses apparent on averages of rectified data only. As can be seen in both examples shown, excitatory effects are obvious on averages of rectified sweeps but not on the non-rectified averages of the same 30 sweeps. The vertical lines across both traces are positioned at the time when the stimulus was applied. IC – iliocostalis lumborum, LM – lumbar multifidus.

There is no reason to suspect that the activity identified on the rectified data was anything other than an increase in EMG activity at the appropriate latency. The most plausible explanation for this phenomenon is that the reflex responses in the 30 traces which make up each average were asynchronous and of differing character. Such
diverse traces would lead to an ill-defined reflex being formed on the non-rectified average. However reflexes which are asynchronous and of varying character should still show as a consistent increase in activity within the same period, and should therefore be apparent on rectification. These responses were therefore included as being reflexes.

3.1.3 Measurement of reflex amplitude.

Measurement of the amplitude of reflexes has been undertaken in a variety of ways. Ferbert et al. (1992) along with many other authors, have used absolute measures in terms of voltage of the peak to peak amplitude of the non-rectified reflex waveform. Zedka et al. (1999) compared the mean amplitude of a short latency reflex induced in the erector spinae muscle with mean EMG activity over the same time period recorded immediately before a stimulus. Evans et al. (1991) Jenner & Stephens (1982) Evans et al. (1990) Issler & Stephens (1983) and Burke et al., (1991) have all expressed the change in area during the period of reflex modulation as a proportion of the area of background EMG activity when analysing musculo-cutaneous reflexes. Recently, Wang et al. (2001) expressed the peak to peak amplitude of a reflex measured from non rectified data relative to the mean background EMG from the same data when rectified. In all these studies the degree of modulation was compared between the same reflex waveforms, within the same muscle, under different conditions.

Thus, in order to compare the degree of reflex modulation between the different trunk muscles, it is important to compare like with like. The first difference encountered between reflexes in different muscles, was a variation in the level of mean background EMG activity in these muscles. On occasions, even the level of activity between left and right pairs of muscles varied substantially. This difference would be likely to
produce reflexes of different absolute size in different muscles. This is due to the automatic gain compensation, whereby the size of a reflex remains approximately the same proportion of the ongoing EMG activity within the muscle being recorded from (Harrison & Taylor, 1981; Matthews, 1986; Prochazka, 1989). The comparison of the peak to peak amplitudes of reflexes in different muscles by this method, would therefore be meaningless. In fact, as shown in figure 3.3, direct comparisons of the reflex amplitudes in different muscles can produce opposite results when using absolute values, compared to referencing the size of the reflex to the background EMG activity.

Figure 3.3. Comparing methods of measuring the amplitude of excitatory reflexes. a) Averages of non-rectified data, and b) averages of rectified data in the left and right internal oblique muscles (IO) in response to tapping medial to the left anterior superior iliac spine. Averages of non-rectified data in a) are measured peak to peak with the values in microvolts. In b) the maximum value of the reflex when rectified and then averaged, relative to the mean background EMG activity, and the area of the reflex relative to a similar time span of the area of background EMG activity, are shown. These comparisons show the right IO to be larger when expressed relative to the levels of EMG activity, and the left IO to be larger when measuring absolute peak to peak values.
Having established that comparison of the amplitude of reflexes in different muscles requires normalisation to the level of on going EMG, the character of the different reflexes also need to be taken into account. The waveforms of the reflexes in different muscles often differed, for instance one reflex may be biphasic and another triphasic. In addition on occasions the effect of rectifying the traces prior to averaging had different effects on the third part of triphasic reflexes in two different muscles, and this is illustrated in figure 3.4.

![Figure 3.4](image)

Figure 3.4. Comparing biphasic and triphasic average waveforms of non-rectified traces, with the same traces rectified and then averaged. The examples shown are short latency reflexes in the left and right internal oblique muscles (IO) resulting from tapping the right IO tendon in both subjects. These are averages of non-rectified data (upper traces) and averages of rectified data (lower traces). The comparison between the reflexes in the left and right muscles, and where the reflex starts and finishes, highlights the difficulties in measuring the size of the reflex by relative areas, or mean values. The horizontal dashed lines represent the mean EMG activity prior to the tap being applied, and the dashed vertical lines identify the start and finish of the reflexes when rectified. 10ms of pre tap EMG activity is included for reference and the onset of the tap is obvious in both subjects by the stimulus artifact, of each pair.
If the point at which the whole reflex returns below the ongoing EMG level is defined as the end of the reflex, this would result in reflexes of different time courses. This will affect the use of mean or area of the reflex relative to the background mean EMG activity in two ways. Firstly, if the comparison is between a biphasic and a triphasic waveform, then the third part of the wave, which is usually the smallest, will reduce the relative mean or area of that reflex compared to the biphasic wave. This may alter which reflex is measured as the larger. Secondly, rectification and then averaging of traces which formed triphasic non-rectified average waveforms does not produce a uniform effect on the third part of the wave resulting in both different time courses and amplitudes, both of which will affect the relative values measured (figure 3.4, subject 2).

It is for these reasons that the maximum value of the rectified and averaged reflexes relative to the mean background EMG activity, as used by Burke et al., (1989) and Gibbs et al., (1995), was used in this study. Whilst it is accepted that using the maximum value as a measure of the amplitude of a reflex excludes other parts of the waveform, it is the only consistent characteristic apparent in all the reflexes evoked which may be directly compared between them.

3.1.4 Measurement of reflex latencies.

The latencies of the excitatory reflex responses were identified visually from the non-rectified averaged data, as the first clear deflection from the background noise. As the electromechanical delay from the digital stimulus to the onset of the tap was less than 1/10th of 1ms this measurement is a good reflection of the true latency from the first displacement of the muscle tissue to the beginning of the reflex waveform. The non-rectified traces were used to measure the latency as rectifying and then averaging the
traces sometimes altered the point of the first clear deflection. This most commonly resulted in a longer measured latency. This effect has been previously noted (Sartucci et al. 1999).

One other factor affecting the measurement of reflex latency was the close proximity of the tap applied to the muscles relative to the recording electrodes. A large stimulus artifact was often evident in the average traces. On occasions this was of short duration and originated from the electrical pulse driving the tapper. Sometimes an artifact of longer duration was seen, the origin of which is likely to be from the mechanical insult creating an electrical signal by the piezoelectric effect, which is detected by the surface electrodes. Occasionally this latter effect encroached onto the beginning of the short latency reflex waveform. However, this encroachment was rarely seen on all individual sweeps. Therefore, when this was obvious on the average reflex trace, the latency was measured from the individual sweeps in which the artifact did not encroach on the reflex, (never less than 50% of sweeps). In a small number of experiments when there was consistent encroachment of the artifact on the reflex response in all or the majority of sweeps, the data was discarded.
4 RESULTS 1 –
SHORT LATENCY REFLEXES BETWEEN THE
ABDOMINAL OBLIQUE MUSCLES.

4.1 Homonymous stretch reflexes in EO and IO.

Short latency reflex responses in the EO muscle were evoked in response to tapping the muscle on the proximal muscle belly in all muscles tested (22/22, 11 subjects) with a mean amplitude of $374\pm60\%$ (mean±SEM) (figure 4.1a). Similarly short latency homonymous reflex responses in the IO muscle were evoked in all muscles tested (40/40, 20 subjects) in response to tapping on its insertion medial to the ASIS with a mean amplitude of $985\pm147\%$ (figure 4.1b). In most subjects the responses of both muscles were apparent on single sweeps (figure 4.1c&d).
4.2 Heteronymous short latency reflex activity between the abdominal oblique muscles.

4.2.1 Reflex connections between the ipsilateral EO and IO.

Tapping the EO muscle belly consistently produced a short latency reflex in the IO muscle (95%, 19/20 experiments, figure 4.2), with an average size of 132±18%, this being 35% of the size of the iEO homonymous reflex. In addition, tapping medial to the ASIS on the IO tendon produced a response in iEO in all experiments (20/20) with an amplitude of 369±69% (figure 4.3)
Figure 4.2. Heteronymous reflexes from the external oblique (EO) to the ipsilateral internal oblique (IO). The point tapped on the muscle is illustrated with an X and the position of the surface electrodes recording the response as pairs of black dots. The upper electrodes are detecting from the EO muscle and the lower pair from the IO muscle. The traces on the right are non rectified averages of 30 sweeps, and the tap was applied at the beginning of the traces.

Figure 4.3. Heteronymous reflexes from the ipsilateral internal oblique (IO) to the ipsilateral external oblique (EO). The point tapped is illustrated with an X and the position of the surface electrodes recording the response as pairs of black dots. The upper electrodes are detecting from the EO muscle and the lower pair from the IO muscle. The traces on the right are the non-rectified average of 30 sweeps, and the tap was applied at the beginning of the trace.
4.3 Reflexes between contralaterally positioned abdominal muscles.

4.3.1 Reflex connections between the EO and IO on opposite sides.

Short latency reflexes in crIO when tapping on the iEO occurred in 75% of the experiments carried out (15/20, figure 4.4) with an amplitude of 166±39%. Tapping medial to the ASIS on iIO also evoked short latency reflexes in the crEO but with a greater frequency of occurrence (95% of the time, 19/20) and an amplitude of 320±63% (figure 4.5).

4.3.2 Reflex connections between the ipsilateral EO and the contralateral EO.

The reflexes between homologous EO muscles (iEO and crEO) occurred 82% of the time (18/22) but were often small and averaged 129±21%, (figure 4.6 & table 4.1).
Figure 4.4. Heteronymous reflexes in the contralateral internal oblique (crIO) when tapping the external oblique (EO). The point tapped on the EO muscle belly is illustrated with an X, and the position of the surface electrodes detecting the response in the right EO and left IO muscles as pairs of black dots. The traces on the right are the non-rectified average of 30 sweeps. The tap was applied at the beginning of the trace.

Figure 4.5. Heteronymous reflexes in the contralateral external oblique (EO) when tapping the internal oblique (IO) muscle. The point tapped is illustrated with an X, and the position of the surface electrodes detecting the response in the left EO and right IO muscles as pairs of black dots. The traces on the right are the non-rectified average of 30 sweeps. The tap was applied at the beginning of the trace.
Figure 4.6. Heteronymous reflexes in the contralateral external oblique (crEO) when tapping the ipsilateral external oblique (EO) muscle. The point tapped on the EO muscle belly is illustrated with an X, and the position of the surface electrodes detecting the response in the left and right EO muscles as pairs of black dots. The traces on the right are the non-rectified averages of 30 sweeps. The tap was applied at the beginning of the trace, and in this instance the stimulus artifact is large and long lasting in the homonymous trace, but decays prior to the onset of the homonymous reflex.

4.3.3 Reflex connections between the ipsilateral IO and the contralateral IO.

As outlined in the Introduction it was to be expected that the reflex connections between the muscles that are attached across the midline anteriorly, would show heteronymous reflex connections to aid co-contraction. However, the homologous IO muscles are not connected anteriorly across the abdomen but as is apparent in figure 4.7, the reflex in crIO when tapping the iIO is substantial.
Figure 4.7. Heteronymous reflexes in the contralateral internal oblique (crIO) muscle when tapping internal oblique (IO). The point tapped on the IO muscle/tendon is illustrated with an X, and the position of the surface electrodes detecting the response in the left and right IO muscles as pairs of black dots. The traces on the right are the non-rectified average of 30 sweeps. The tap was applied at the beginning of the trace.

In fact, not only is the homonymous reflex in IO the largest reflex observed in any of the trunk muscles tested (985±147%), the reflex in the crIO muscle is almost as large (807±89%, figure 4.7, table 4.2). Indeed the difference between them is not significant (p=0.12, see chapter 6).
<table>
<thead>
<tr>
<th>Point tapped</th>
<th>Muscle recorded from</th>
</tr>
</thead>
<tbody>
<tr>
<td>EO</td>
<td>Ipsilateral External Oblique</td>
</tr>
<tr>
<td>Frequency of occurrence (%)</td>
<td>100 (22/22)</td>
</tr>
<tr>
<td>Amplitude as % of ipsilateral EO reflex</td>
<td>34</td>
</tr>
</tbody>
</table>

Table 4.1. Frequency and amplitude of reflexes induced in the external oblique and internal oblique muscles in response to tapping the muscle belly of external oblique. Data is mean±SEM, [range]. The amplitude is measured from data rectified then averaged, with the maximum expressed as a percentage of the mean EMG activity prior to the tap being applied.
<table>
<thead>
<tr>
<th>Point tapped</th>
<th>Muscle recorded from</th>
</tr>
</thead>
<tbody>
<tr>
<td>IO</td>
<td>Ipsilateral External Oblique</td>
</tr>
<tr>
<td>Frequency of occurrence (%)</td>
<td>100 (20/20)</td>
</tr>
<tr>
<td>Amplitude as a % of ipsilateral IO reflex</td>
<td>37</td>
</tr>
</tbody>
</table>

Table 4.2. Frequency and amplitude of reflexes induced in the external oblique and internal oblique muscles (IO) in response to tapping the IO medial to the ASIS. Data is mean±SEM [range]. The amplitude is measured from data rectified then averaged, with the maximum expressed as a percentage of the mean EMG activity prior to the tap being applied.
4.3.4 *Summary of short latency excitatory reflexes between the abdominal oblique muscles.*

The frequency of occurrence of each of the eight reflex pathways described so far is never less than 75%, with those involving the IO afferents occurring most frequently (figure 4.8, tables 4.1 & 4.2).

![Figure 4.8](image)

**Figure 4.8.** Percentage occurrence of short latency excitatory responses between the external oblique (EO) and internal oblique (IO) muscles. (i – ipsilateral, cr – contralateral).

As illustrated in figure 4.9 when tapping medial to the ASIS on the IO muscle, the responses within both ipsilateral and contralateral oblique muscles are larger than those evoked when tapping the EO muscle in isolation. The only exception to this is the homonymous EO reflex.
Figure 4.9. Average amplitudes of the short latency reflexes evoked in the external oblique (EO) and internal oblique (IO) muscles in response to tapping EO in isolation, and on IO medial to the anterior superior iliac spine. Apart from the reflex evoked in the ipsilateral EO muscle (iEO), the reflex in each muscle is always larger when tapping on the IO muscle. (i – ipsilateral, cr – contralateral).

4.3.5 Which afferents predominate when tapping medial to the ASIS?

As both the EO tendon and IO muscle underlie the point at which the tap is applied medial to the ASIS, it may be that both EO and IO muscles will be perturbed when the tap is applied. The EO tendon does not attach to the ASIS at this point whereas the IO tendon does (sees section 1.4.6) and it therefore seems likely that the IO will be perturbed more so evoking more IO afferent activity. Notwithstanding this, an attempt to identify the relative contribution of EO and IO afferents to the reflex activity evoked in each muscle was modelled. For the purposes of the model it was assumed that tapping a) medial to the ASIS and b) on the EO muscle produced equal amounts of afferent activity from the EO muscle. The amplitude of the reflex evoked in a given
muscle when tapping on EO was then subtracted from the amplitude of the reflex evoked in the same muscle when tapping medial to the ASIS. The remaining amplitude thus represents the contribution of the IO afferents to the reflex in a given muscle. The effect of this subtraction is presented in figure 4.10 and table 4.3. The most obvious effect is the dramatic reduction in the amplitude of the reflex in iEO relative to the reduction in the amplitude of the reflexes in the other muscles, particularly crEO.

Figure 4.10. The relative contribution of external oblique (EO) and internal oblique (IO) muscle afferents to both homonymous and heteronymous reflexes between the EO and IO muscles. The front row is the amplitude of the short latency responses when tapping EO in isolation and the back row when tapping medial to the ASIS (i.e. putatively both EO and IO). The middle row is the EO effect subtracted from the putative EO/IO effect for each pair of muscles. This quantifies the respective contributions of each set of muscle afferents, and highlights the great potency of the IO reflex afferents. It also highlights the much reduced IO afferent effect on the iEO relative to crEO (see text for full explanation).
Table 4.3. Amplitudes of the short latency reflex responses in the external oblique and internal oblique muscles when tapping medial to the ASIS minus the size of the reflex evoked in the same muscle when tapping the EO muscle.

<table>
<thead>
<tr>
<th></th>
<th>Ipsilateral External Oblique</th>
<th>Crossed External Oblique</th>
<th>Ipsilateral Internal Oblique</th>
<th>Crossed Internal Oblique</th>
</tr>
</thead>
</table>

If the underlying assumption of equal EO afferent activity from tapping at both points is correct this indicates that the IO muscle afferents do not evoke substantial heteronymous reflexes in iEO, whereas they do in crEO. This contrasts with the comparable reflex amplitudes in the iIO and crIO muscles when evoked by IO afferents. In addition, as will be demonstrated in Chapter 5 the amplitude of the reflexes in the ipsilateral RA (iRA) and contralateral RA (crRA) muscles when tapping medial to the ASIS is symmetrical. It therefore seems unlikely that the distribution of reflex actions of IO afferents is symmetrical to the iIO and crIO and the iRA and crRA, but not to both EO muscles. A more plausible interpretation is that when tapping medial to the ASIS the afferent activity evoked is predominantly from the IO muscle, and not the EO. Interpreting the data in this way results in a symmetrical distribution of reflex actions of IO afferents to the IO, EO and RA muscle pairs on both sides. Therefore, a tap applied medial to the ASIS is henceforth assumed to evoke muscle afferent activity predominantly from the IO muscle. This allows comparison of the effectiveness of the afferents from EO with those from IO to be undertaken with some confidence. Such a comparison is illustrated in figure 4.11. The thickness of the arrows in figure 4.11 indicates the strength of the reflexes from the EO afferents (blue arrows) and IO afferents (red arrows).
Figure 4.11. Summary of the reflexes evoked in both internal oblique (IO) and external oblique (EO) muscles when tapping a) EO and b) IO. Reflexes of greater amplitude are indicated by thicker arrows, and the average amplitude by the adjacent text. The muscle tapped is in bold.
4.3.6 Relative size of ipsilateral and contralateral short latency responses.

As illustrated in figure 4.12, the relative amplitudes of the crossed reflexes between the muscles attached across the abdomen anteriorly, apart from ilO to crlO, are almost invariably smaller than the ipsilateral reflexes. However, those between ilO and crlO are not only large when compared individually but are often larger contralaterally (9/20, from the paired data presented).

Figure 4.12. Comparison of the amplitudes of the ipsilateral and contralateral reflexes between four different pairs of external oblique (EO) and internal oblique (IO) muscles. The amplitude of the reflexes in 10 subjects (20 muscle pairs), when tapping the EO muscle belly and the IO muscle are shown. The main contrast is that the relative size of the contralateral IO (crlO) reflex when tapping the ipsilateral IO (ilO) is often larger than the ilO homonymous reflex, whereas in all other pairs the contralateral reflex is almost invariably smaller than the ipsilateral reflex.
4.4 Latencies of the ipsilateral and crossed abdominal oblique reflexes.

4.4.1 Homonymous reflex latencies.

The average latency of the EO homonymous reflex was 14.7±0.3ms with the earliest recorded latency being 12.5ms. In contrast, the latency of the IO homonymous reflex was 15.9±0.2ms with the earliest recorded latency being 13.0ms.

Estimation of the conduction velocity of afferent and efferent axons mediating the homonymous reflex pathways.

To estimate the conduction velocity of the EO and IO homonymous reflex pathways the measured latencies can be used together with the conduction distance of the peripheral nerve supplying that muscle. To calculate the conduction distance the two end points of the peripheral nerve supply and its course, need to be known. In this instance the position of the surface electrodes, the course of the thoracic spinal nerves which supply the EO and IO muscles and the position of each segment of the spinal cord levels relative to the vertebral column (Carpenter, 1985) taken from human cadavers, are known. However, the location of EO and IO motoneurone pools within the spinal cord is known only in the cat. In three studies of feline abdominal muscle motoneurone pool organisation (Holstege et al. 1987; Miller, 1987; Tani et al. 1994) the EO motoneurone pool has been shown to extend from the mid to the end of the thoracic spinal cord, whilst the IO motoneurone pool is primarily situated in the upper lumbar segments and the last few thoracic segments. As this is the only data of EO and IO motoneurone pool location available, the assumption was made that the motoneurone pools in man are similarly positioned. Therefore, with all parts of the EO and IO peripheral reflex
pathways known, the conduction velocities of each can be estimated. To construct the model using these distances the following assumptions also need to be made; i) the afferent and efferent pathways travel together within the same nerve and have equal conduction velocities (Macefield & Gandevia, 1992), ii) that the earliest latency of these reflexes is monosynaptic (Burke et al., 1984; Macefield & Gandevia, 1992), and therefore 1ms is allowed for the synaptic delay within the spinal cord, and iii) that there is a delay of 1ms at the neuromuscular junction.

The conduction velocity of the EO homonymous reflex response.

The distance from the recording site over the EO muscle belly on the anterolateral abdominal wall, around the abdominal wall and the thoracic cage to the likely position of the motoneurone pool at the vertebral level of T8, was measured on five human skeletons. The distance measured was 0.33±0.01m. Therefore, the conduction distance is 0.33*2=0.66m when allowing for both afferent and efferent pathways. The conduction velocity was then calculated as indicated above from the average latency of 14.7ms, less 1ms for synaptic delay, and 1ms for the delay at the neuromuscular junction (i.e.12.7ms). With the peripheral conduction distance of 0.66m, this gives a value of 52m/s. Using the shortest reflex latency the conduction velocity is calculated at 63m/s.

A previous study of the short latency response to tapping the EO muscle (Macefield & Gandevia, 1992) reported a latency of 13.7ms with a conduction velocity of 56.2m/s. The small difference between these calculated velocities is probably due to both the shorter latency and the different measurement techniques used to estimate conduction distance. In the present study the measurements were taken very close to the bone on skeletons, whereas the measurements taken by Macefield & Gandevia, (1992) were on
human subjects with all tissue intact. This gives a larger circumference of the abdomen and thorax, and therefore a longer peripheral conduction distance.

The conduction velocity of the afferent and efferent axons mediating the IO homonymous reflex response.

Measurements for the IO homonymous pathway were made in the same way as for EO. The distance from the EMG site over the IO muscle, around the abdomen and thorax to the vertebral level T10, (data taken from the studies in the cat and man, as for EO), is 0.35±0.01m. When allowing for both afferents and efferents this is 0.7m±0.02. By subtracting 1ms for the monosynaptic central delay and 1ms for the neuromuscular junction delay in the periphery, the resultant conduction velocity is calculated to be 50m/s. Using the shortest measured latency the conduction velocity is calculated to be 62m/s. These estimated conduction velocities of the afferent and efferent fibres mediating the homonymous IO reflex, are consistent with those of other la muscle afferents in humans, (Magladery & McDougall, 1950; Shefner & Logigian, 1994). This close fit therefore suggests that the homonymous IO reflex is likely to be monosynaptically mediated.

4.4.2 Latencies of the heteronymous reflexes between the EO and IO muscles of both sides.

The latencies of the heteronymous reflexes to tapping the abdominal oblique muscles range from 17.4 – 19.6ms, (figure 4.13 & table 4.3).
Figure 4.13. Latencies of short latency reflexes in the external oblique (EO) and internal oblique (IO) muscles when tapping the EO and IO muscles. Measurements are mean±SEM. i – ipsilateral, cr – contralateral

<table>
<thead>
<tr>
<th>Muscle recorded from</th>
<th>Ipsilateral</th>
<th>Crossed</th>
<th>Ipsilateral</th>
<th>Crossed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>EO</td>
<td>EO</td>
<td>IO</td>
<td>IO</td>
</tr>
<tr>
<td>Tap EO muscle belly</td>
<td>14.7±0.3</td>
<td>19.6±0.4</td>
<td>17.9±0.8</td>
<td>19.6±0.5</td>
</tr>
<tr>
<td></td>
<td>[12.5-17.3]</td>
<td>[17.4-23.2]</td>
<td>[13.3-24.4]</td>
<td>[16.6-22.1]</td>
</tr>
<tr>
<td>Tap IO medial to the ASIS</td>
<td>16.6±0.5</td>
<td>18.5±0.6</td>
<td>15.9±0.2</td>
<td>17.4±0.2</td>
</tr>
<tr>
<td></td>
<td>[13.3-22.1]</td>
<td>[15.5-24.9]</td>
<td>[13.3-19.5]</td>
<td>[15.0-21.2]</td>
</tr>
</tbody>
</table>

Table 4.4. Latencies of the reflexes evoked in the external oblique (EO) and internal oblique (IO) muscles in response to tapping the muscle belly of EO and IO. Data is mean±SEM [range]. The latency is measured from records of the non-rectified average.
Heteronymous abdominal oblique muscle reflexes evoked from EO afferents are longer in latency than the EO homonymous response as follows; 2.6ms to the iIO muscle, 4.7ms to the crEO, and 5.2ms to the crIO. Heteronymous abdominal oblique reflexes evoked from IO afferents are also longer than the homonymous iIO reflex as follows; iEO 0.7ms, crEO 2.6ms longer and crIO 1.5ms. However, the differences between the crossed reflex latencies in each muscle are less when tapping IO than when tapping EO (crIO 1.5ms v 5.2ms and crEO 2.6ms v 4.7ms). Of these the difference between the latencies in the iIO and crIO when tapping IO is the shortest at 1.5ms. As the crIO motoneurone pool is positioned contralaterally in the spinal cord relative to the iIO motoneurone pool, the distance for the iIO afferents to traverse to affect the contralateral motoneurones is greater. Bearing this in mind, the iIO afferent pathway across the spinal cord to the crIO may be monosynaptic in nature. In order to consider this further, the following sections highlight the relationship between the amplitudes of these responses and their relative latencies.

4.4.3 Association between the latency and amplitude of reflexes between the EO and IO.

The relationship between the latency and the amplitude of the four ipsilateral and crossed responses is exemplified in figure 4.14. In figure 4.14a the responses in both iEO and crEO muscles to tapping the EO are shown. The latency of the crossed response is longer than that of the ipsilateral response, and the amplitude is smaller. A similar pattern is seen in the responses observed in the iEO and crIO when tapping the EO muscle belly (figure 4.14b), and in the iIO and crEO when tapping the IO muscle (figure 4.14c).
Figure 4.14. Comparisons of both latency and amplitude of the ipsilateral and crossed reflexes between external oblique (EO) and internal oblique (IO) muscles. (In all cases the reflex with the earliest latency is the ipsilateral response). a) Tapping EO showing iEO and crEO short latency reflexes. b) Tapping EO showing iEO and crIO reflexes. c) Tapping IO showing iIO and crIO reflexes. d) Tapping IO showing iIO and crIO reflexes. Only in d) between the iIO and crIO muscles are the amplitudes of the reflexes comparable. (i-ipsilateral, cr- contralateral).

In contrast, the responses in the iIO and crIO muscles when tapping over the iIO, can be of comparable amplitude, and this is associated with the smaller difference in latency of iIO and crIO reflexes (1.5 ms, figure 4.14d). In fact, as shown previously in figure 4.12 the relative amplitude of the reflex in crIO when tapping iIO can be larger than the iIO reflex evoked from the same stimuli. This point is further highlighted in one subject in figure 4.15.
Figure 4.15. Short latency reflexes in the ipsilateral (black) and contralateral (red) internal oblique muscles in response to tapping the IO on one side. The two reflexes (average of 30 sweeps) are superimposed in b) to show the minimal difference in latency between them and the greater amplitude of the crossed reflex. In a&c five individual sweeps recorded simultaneously which contributed to the two reflexes in b are shown. Those in a) are the ipsilateral homonymous reflex, and those in c) are the contralateral crossed reflex.

Five individual traces collected simultaneously in iIO and in crIO are shown in figure 4.15a&b. The average responses from the same muscles in the same experiment collected from 30 sweeps are shown in figure 4.15b. As is obvious and highlighted by the red colour of the crIO responses, not only are both ipsilateral and contralateral reflexes obvious on single sweeps, but in this instance the individual reflexes in the crIO are clearer than those in iIO.

Further attempts were made to investigate whether a shorter latency of the crIO reflexes relative to that of iIO was related to a larger amplitude of the crIO reflex. It has previously been observed that an increase in amplitude of a reflex is associated with a reduction in latency of that reflex (Ratto et al. 1986). Specifically therefore, it might be expected that the difference in latency between iIO and crIO would be less the larger the
amplitude of the crIO reflex relative to that in iIO. However, whilst this did seem to be the case in a number of instances no obvious relationship was evident when all the data was considered.

4.4.4 The effect of vibration on the ipsilateral and crossed IO reflexes.

The minimal difference in latency of the crIO reflex relative to that in iIO and the comparable amplitude of both these reflexes when tapping IO indicates that both reflexes may be evoked by similar connections. This possibility was further considered by vibrating the iIO muscle at 50hz as it was being tapped. Vibration superimposed on a muscle being stretched in this manner has been shown previously to reduce the size of the homonymous short latency reflex being evoked, possibly via presynaptic inhibition of la afferents onto la afferents (reviewed by Stein, 1995, however see discussion p177-178). If the reflex connections to crIO are similar to those of iIO then it might be expected to reduce in amplitude in a similar manner to the iIO response.

As expected vibration reduced the size of the iIO response in five subjects to a mean value of 63±11% of the reflex amplitude without vibration (figure 4.16). In addition, vibration reduced the crIO response to a mean level of 74±5% of the reflex amplitude without vibration. This effect supports the suggestion that the response in the crIO muscle is mediated via the same pathways as that to iIO.
Figure 4.16. Tapping ± vibration on the IO muscle and the effect on the ipsilateral and crossed internal oblique reflexes evoked. Both ipsilateral and crossed reflexes are reduced during vibration and slightly potentiated upon cessation of the vibration. The tap was applied at the beginning of the trace.
4.5 Summary of short latency excitatory reflex connections between the abdominal oblique muscles.

Short latency homonymous and heteronymous reflexes have been shown to exist between the abdominal oblique muscles of both sides (EO and IO) in response to tapping the EO and IO muscles. These reflexes occurred in 75% to 100% of the experiments undertaken. Those evoked by IO afferents occurred more frequently than those from EO afferents (95% - 100%) and are of greater amplitude. The heteronymous reflex with the largest amplitude was in the crIO when tapping the iIO, this being of comparable size to the reflex evoked in iIO.

The conduction velocities calculated from the conduction distances of both afferent and efferent pathways fall into the expected range of short latency reflexes evoked from Ia muscle afferents. This confirms that the pathways are spinally mediated. The latency of all the heteronymous reflexes in the EO and IO muscles on both sides, relative to the respective homonymous responses, is never more than 5ms. The latency of the reflex in the crIO relative to that in iIO when tapping IO is particularly short at 1.5ms. This raises the possibility that the pathway across the spinal cord may be monosynaptic. The similarity in size and behaviour of the iIO and crIO reflexes would support this notion.
5 RESULTS 2 -
SHORT LATENCY REFLEXES INVOLVING THE RA MUSCLE AND THE EO AND IO MUSCLES.

Short latency reflexes were observed from RA afferents to RA, EO and IO muscles on both sides. In addition, reflex responses evoked in the RA muscle from RA, EO and IO afferents on both sides were also observed.

5.1 Short latency reflexes in the RA muscle in response to tapping the RA muscle.

Short latency reflexes were evoked in the RA muscle when tapping the proximal aspect of the RA muscle in standing, and these occurred 76% of the time (13/17, table 1, figure 5.1 & 5.2). The experiment was also undertaken while leaning back. This raised the level of background EMG fourfold and this revealed a reflex 100% of the time (32/32, figure 5.2).

Figure 5.1. Homonymous reflex response in the rectus abdominis (RA) muscle. The reflex is evoked by tapping the upper portion of the RA muscle. The trace on the left is the average of 30 sweeps, and those on the right are five of the sweeps contributing to the average trace.
The amplitude of the homonymous RA reflex was 125±20% in standing and 204±27% when leaning back. The difference between these was not significant (t test p=0.082).

5.2 Short latency reflexes in the contralateral RA muscle to tapping the ipsilateral RA.

In addition to evoking a short latency reflex in the homonymous RA, a short latency excitatory reflex was also evoked in the crRA when tapping the RA muscle (figure 5.2). This occurred approximately 50% of the time (10/20) in upright standing, and 71% of the time (23/32) when leaning back. As for the homonymous reflex this crossed response was often obvious on single sweeps. The average amplitude of the crossed response relative to the background mean EMG level was 87±11% in standing, and 120±19% when leaning back, but this difference was not significant (p=0.135).

![Diagram of short latency reflexes in both ipsilateral and contralateral rectus abdominis muscles](image)

Figure 5.2. Short latency reflexes in both ipsilateral and contralateral rectus abdominis muscles (average of 30 sweeps) when tapping one RA muscle. The point tapped is illustrated as an X, whilst the position of the electrodes are signified by the pairs of black dots. The reflex in subject 1 was evoked in standing whereas those in subjects 2 & 3 were evoked when leaning back (to raise the level of background EMG in both muscles).
The size of the crossed reflex relative to the ipsilateral reflex was 70% in standing, and 59% when leaning back. The data of the frequency of occurrence, amplitude and the latencies of these reflexes are detailed in table 5.1. The reflex latency of the homonymous reflex in RA was $20.2\pm 0.7\text{ms}$ in upright standing and $20.9\pm 0.6\text{ms}$ whilst leaning back but the difference between these is not significant ($p=0.38$).

<table>
<thead>
<tr>
<th></th>
<th>Frequency (%)</th>
<th>Amplitude</th>
<th>Reflex latency</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>% (±SEM)</td>
<td>range (±SEM)</td>
</tr>
<tr>
<td><strong>Standing</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RA homonymous</td>
<td>76 (13/17)</td>
<td>125 (20)</td>
<td>53-275 (0.7)</td>
</tr>
<tr>
<td>RA crossed</td>
<td>50 (10/20)</td>
<td>87 (11)</td>
<td>52-166 (1.0)</td>
</tr>
<tr>
<td><strong>Leaning back</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RA homonymous</td>
<td>100 (32/32)</td>
<td>204 (27)</td>
<td>46-705 (0.6)</td>
</tr>
<tr>
<td>RA crossed</td>
<td>56 (18/32)</td>
<td>120 (19)</td>
<td>38-347 (0.6)</td>
</tr>
</tbody>
</table>

Table 5.1. Frequency of occurrence, amplitudes and latencies of the short latency reflexes in both rectus abdominis (RA) muscles to tapping the RA muscle.
5.3 **Short latency reflexes in the EO muscles when tapping the RA muscle.**

When tapping the RA muscle proximally with subjects in standing, short latency reflexes were observed in both the iEO and crEO muscles. Occasionally, a short latency reflex in the EO muscle was obvious when the homonymous reflex in RA was weak or non-existent (figure 5.3). The short latency responses when tapping the RA muscle occurred in iEO 42% of the time (5/12) and in crEO 50% of the time (6/12). The amplitude of the reflex in iEO was 104±17% and that in the crEO was 88±15% (table 5.2).

![Figure 5.3](image)

**Figure 5.3.** Short latency reflexes in both external oblique muscles (EO) when tapping the ipsilateral rectus abdominis (RA) muscle. Of note is the small response in the homonymous RA muscle compared to the responses in the EO muscles. The point tapped is illustrated by an X, and the detecting electrodes as pairs of black dots.
5.4 Short latency reflexes in the IO muscle when tapping the RA muscle.

Short latency reflexes were evoked in both iIO and crio muscles in response to tapping the RA, as shown in figure 5.4. These reflexes occurred in 50% of experiments (10/20) ipsilaterally, and in 48% of experiments (10/21) contralaterally. The amplitude of these reflexes were on average both less than 100% (iIO 92±23%, crIO 84±13%, table 5.2).

![Figure 5.4](image.png)

Figure 5.4. Short latency reflexes in the ipsilateral rectus abdominis (RA) muscle and both the ipsilateral and contralateral internal oblique (IO) muscles, when tapping the RA muscle belly proximally. The point tapped and the muscle recorded from are illustrated as an X, and pairs of black dots respectively.

<table>
<thead>
<tr>
<th></th>
<th>Frequency (%)</th>
<th>Amplitude</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>n</td>
<td>RA - ipsilateral EO</td>
</tr>
<tr>
<td>n</td>
<td>5/12</td>
<td>42</td>
</tr>
<tr>
<td>RA - crossed EO</td>
<td>6/12</td>
<td>50</td>
</tr>
<tr>
<td>RA - ipsilateral IO</td>
<td>10/20</td>
<td>50</td>
</tr>
<tr>
<td>RA - crossed IO</td>
<td>10/21</td>
<td>48</td>
</tr>
</tbody>
</table>

Table 5.2. Frequency of occurrence and amplitudes of short latency reflexes in the external oblique (EO) and internal oblique (IO) in response to tapping the rectus abdominis muscle (RA) with subjects in upright standing.
5.5 Short latency reflexes in the RA muscles in response to tapping the EO muscles.

A reflex was seen in the iRA in response to tapping the EO muscle 55% of the time (5/9, table 5.2), whilst the response in the crRA occurred 17% of the time (2/12, table 5.2). The amplitude of the heteronymous reflex in the iRA muscle evoked from EO afferents was 131±12% whilst that in the crRA was 78±31%. Examples of these are shown in figure 5.5. Although the difference between these two amplitudes is not large, a response occurs much more frequently in iRA than crRA. Thus, the reflexes evoked in the RA muscles from the EO afferents are more obvious ipsilaterally.

Figure 5.5. Short latency reflexes in the rectus abdominis muscle (RA), when tapping the external oblique muscle (EO) with the subjects standing. Subject 1 shows the more typical isolated response in the ipsilateral RA, whilst for subject 2 the only instance when both RA muscles responded is illustrated. The point tapped is illustrated by an X and the electrodes as pairs of black dots.

5.6 Short latency reflexes in the RA muscles in response to tapping the IO muscle.

Short latency reflexes were also observed in the RA muscles in response to tapping the IO muscle medial to the ASIS (figure 5.6). The reflex in the iRA occurred 87% of the
time (13/15 table 5.2), whilst the reflex in the crRA occurred 75% of the time (15/20 table 5.2). The amplitude of the reflex in the iRA muscle was on average 163±26% (table 5.3), whilst that in crRA was 119±16%, (p=0.08). Of note is that this reflex in iRA was the largest amplitude of the short latency heteronymous reflexes involving RA.

![Diagram of muscle reflexes](image)

Figure 5.6. Short latency heteronymous reflexes in both the ipsilateral and contralateral rectus abdominis muscles (RA) and in the ipsilateral internal oblique (IO) when tapping on IO. The point tapped is illustrated by an X and the electrodes as pairs of black dots.

<table>
<thead>
<tr>
<th></th>
<th>n</th>
<th>Frequency (%)</th>
<th>Amplitude</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>% ±SEM</td>
</tr>
<tr>
<td>EO – ipsilateral RA</td>
<td>5/9</td>
<td>55</td>
<td>131±12</td>
</tr>
<tr>
<td>EO – crossed RA</td>
<td>2/12</td>
<td>17</td>
<td>78±31</td>
</tr>
<tr>
<td>IO – ipsilateral RA</td>
<td>13/15</td>
<td>87</td>
<td>163±26</td>
</tr>
<tr>
<td>IO – crossed RA</td>
<td>15/20</td>
<td>75</td>
<td>119±16</td>
</tr>
</tbody>
</table>

Table 5.3. Frequency of occurrence, and amplitudes of short latency reflexes in the rectus abdominis muscle (RA) to tapping the external oblique (EO) and to tapping the internal oblique (IO) muscle.
5.7 Overview of the frequency of occurrence of short latency reflexes involving the RA muscle.

Figure 5.7 shows the relative frequency with which the reflexes involving the RA muscle occur (whilst excluding those between the oblique muscles for clarity). The two most obvious contrasts are the low frequency of occurrence of reflexes from EO to crRA, and that reflexes evoked from IO afferents occur most frequently.

![Graph showing frequency of occurrence of reflexes](image)

Figure 5.7. Frequency of occurrence of short latency reflexes involving the RA afferents, the RA muscles and the EO and IO muscles. Note that for clarity those reflexes evoked between the EO and IO muscles are excluded.
5.8 Effectiveness of RA muscle afferents in standing and leaning back.

As stated previously, the frequency of occurrence of the reflexes in both iRA and crRA when tapping the RA muscle are increased when leaning back. On the other hand as can be seen in figure 5.8, leaning back did not increase the occurrence of the reflexes from RA to the oblique muscles. In fact, this figure shows a reduced occurrence of the response to the EO muscles. Therefore, whichever starting position is used the occurrence of short latency heteronymous reflex pathways from RA afferents to the oblique muscles is never more than 50%.

![Bar chart showing frequency of occurrence of reflexes in standing and leaning back](image)

**Figure 5.8.** Frequency of occurrence of reflexes to and from the rectus abdominis (RA) muscle in standing and leaning back.
5.9 Comparison of the latencies of short latency reflexes to and from the RA muscle

5.9.1 Conduction velocity of the axons mediating the homonymous reflex in RA.

To estimate the conduction velocity of the RA reflex, the same procedure was followed as for the EO and IO muscles. That is, measurements taken from five skeletons and data on the motoneurone pool location of the RA muscle in cats (Holstege et al. 1987; Miller, 1987; Tani et al. 1994) were used to calculate the RA conduction velocity. The conduction distance for the RA muscle was therefore calculated as follows. The distance from the recording site over the RA muscle belly just lateral to the midline anteriorly, around the abdominal wall and the thoracic cage to the likely position of the motoneurone pool (Holstege et al. 1987; Miller, 1987; Tani et al. 1994) at the vertebral level of T4 (Carpenter, 1985), was measured on five human skeletons. The distance measured was $0.45 \pm 0.02$ m. Allowing for both afferent and efferent pathways, this becomes $0.90 \pm 0.05$. The conduction velocity was then calculated as described in section 4.4 for EO and IO. The average latency of 20.2, minus 1 ms for synaptic delay and 1 ms for the delay at the neuromuscular junction gives a peripheral conduction time of 18.2 ms. The calculated mean conduction velocity is therefore 49 m/s. Using the shortest latency (17 ms) when calculating for the conduction velocity gives a velocity of 60 m/s. These estimates of conduction velocity for fibres mediating RA reflexes compares favourably with those for EO and IO and with measured conduction velocities for low threshold afferent fibres in man (Magladery & McDougall, 1950). That all three estimates of conduction velocity for RA, EO and IO give such similar values, suggests the longer latency for the RA reflex is due to the longer conduction distance.
5.9.2 *Latencies of the heteronymous reflexes involving the RA muscle.*

The latencies of the short latency reflexes involving the rectus abdominis muscle and those evoked in the EO and IO muscles are detailed in table 5.4. They are also shown in figure 5.9 arranged together to allow comparison. The difference in latency between the homonymous RA reflex and that from iRA to crRA reflexes is 2.1ms when leaning back and 2.3ms in standing (table 5.1).

![Diagram showing latencies of reflex connections](image)

Figure 5.9. Latencies of ipsilateral and crossed short latency reflex connections to and from the rectus abdominis (RA) muscle and the external (EO) and internal oblique (IO) muscles. Values are mean± SEM.
The main point of note is that reflexes evoked from RA afferents to the EO and IO are substantially longer than those evoked from afferents of the oblique muscles to the oblique muscles. These differences are significant when compared to IO afferents (p<.001), whilst the small numbers of EO afferent responses (n=3) preclude statistical analysis. The reflexes evoked from both EO and IO afferents are shorter than the homonymous RA reflex (table 5.4). This is likely to be due to the shorter distances that the afferents from the oblique muscles have to travel to the respective levels of the spinal cord.

<table>
<thead>
<tr>
<th>Muscle tapped from</th>
<th>Muscle recorded from</th>
<th>Latency, (mean±SEM ms), [range]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Ipsilateral</td>
</tr>
<tr>
<td>RA</td>
<td>RA</td>
<td>20.1±0.7 [17.0-24.9]</td>
</tr>
<tr>
<td>RA</td>
<td>EO</td>
<td>18.3±2.0 [16.3-20.2]</td>
</tr>
<tr>
<td>RA</td>
<td>IO</td>
<td>19.5±0.7 [16.2-22.4]</td>
</tr>
<tr>
<td>EO</td>
<td>RA</td>
<td>14.5±0.8 [13.6-16.0]</td>
</tr>
<tr>
<td>IO</td>
<td>RA</td>
<td>16.7±0.6 [13.6-20.8]</td>
</tr>
</tbody>
</table>

Table 5.4. Latencies of the short latency reflexes to and from the rectus abdominis (RA) muscle, external oblique (EO) and internal oblique (IO) muscles, in response to tapping each muscle.
5.9.3 The inhibitory effect of vibration on RA reflexes.

As for the reflexes between the iIO and crIO muscles (section 4.4.4) the nature of the reflex between iRA and crRA muscles was investigated using vibration applied to the RA muscle being tapped (n=10). As can be seen in the examples in figure 5.10, the amplitude of both the iRA and crRA short latency reflexes were reduced during vibration. This was true for all subjects tested. This effect is similar to that seen between the two IO muscles when using the same protocol and is consistent with the known effect of vibration on tendon jerks and H reflexes.

![Diagram of short latency reflexes in RA muscle](image)

Figure 5.10. Short latency reflexes in a) the ipsilateral RA and b) the contralateral RA muscle, to tapping with and without superimposed vibration on the muscle being tapped.
5.10 Summary of short latency excitatory reflexes between the RA muscle and the EO and IO muscles.

In addition to the short latency excitatory reflexes reported between the abdominal oblique muscles, short latency reflexes between the rectus abdominis muscles and the EO and IO have also been demonstrated.

Ipsilateral RA to contralateral RA.
The homonymous RA reflex was more difficult to evoke in standing than in EO and IO. When the background level of EMG was raised by leaning back a response was revealed in all RA muscles tested. However, the reflex evoked was still smaller than the EO and IO homonymous reflexes. In addition, tapping the RA evoked short latency excitatory reflexes in crRA more than 50% of the time. The amplitude of these reflexes were more than 50% of the homonymous RA reflex. Vibration reduced the size of both iRA and crRA responses. Such similar behaviour of these reflexes gives more support to the idea of similar synaptic connectivity for both muscles, as was found to be the case between iIO and crIO.

Rectus abdominis to the external oblique and internal oblique muscles.
Reflex connections evoked from RA afferents to the oblique muscles were less frequently observed than between the two RA muscles. However, reflexes in both ipsilateral and contralateral EO and IO were observed in 40% to 50% of the experiments undertaken. The amplitudes of these reflexes ranged from 84% to 104%.
External oblique and internal oblique to rectus abdominis.

Reflexes evoked from EO to RA occurred less frequently (50% to iRA and 9% to crRA) than those evoked from IO to RA (both over 70%). In addition, the EO reflex is more frequently seen in iRA compared to crRA, whereas the reflexes evoked from IO afferents are evenly distributed to both iRA and crRA. This highlights not only the more bilateral effects of IO afferents but the greater frequency of effects generally evoked by IO afferents.

Conduction velocities of axons mediating RA reflexes.

The estimated conduction velocity for the homonymous RA reflex is similar to the estimates for EO and IO muscles. However, the latency of the RA reflex was substantially longer than that for EO and IO and this is probably due to the longer conduction distance and the more proximal position of the RA motoneurone pool. The latencies of all the reflexes involving the RA afferents and RA muscles range from 14.5ms to 22.1ms. The longer latencies of the heteronymous reflexes are not long enough relative to the homonymous reflexes to be anything other than spinally mediated.
This chapter consists of a more detailed analysis of the frequency of occurrence, amplitude and latency of short latency reflex responses of RA, EO and IO muscles.

6.1 Frequency of occurrence of short latency reflexes.

The frequency of occurrence of the short latency reflexes between RA, EO and IO are presented in figure 6.1.

Figure 6.1. Frequency of occurrence of short latency excitatory reflexes between the rectus abdominis (RA) external oblique (EO) and internal oblique muscles (IO) on both sides when tapping each muscle individually.
6.2 Comparison of short latency reflex amplitudes between the different reflexes.

The mean amplitudes of all 18 reflexes between the abdominal muscles calculated using only those occasions on which the response was observed are shown in Figure 6.2. From this it is obvious that the effects between the EO and IO muscles are the largest. The mean amplitude of all the other reflexes calculated in this manner are however similar.

![Graph showing mean amplitudes of short latency reflexes between abdominal muscles.](image)

Figure 6.2. Mean amplitudes of the short latency reflexes between the abdominal muscles. Occasions in which no response were observed are excluded.
6.3 Reflex connections between the abdominal muscles.

Analysis of the frequency of occurrence data would normally be undertaken using the chi squared test, but the comparison groups require values of at least five. As some of the reflexes occurred in 100% of experiments this form of analysis would be meaningless. However the different mean amplitudes of the short latency reflexes can be analysed using statistical testing. As detailed in the Method this was undertaken by including those responses where no effect was observed. This does therefore include both amplitude and frequency of occurrence data and is as previously stated termed 'potency'. Prior to using inferential statistical tests to compare the potency of the different reflexes, any difference between tapping the left and right muscles was compared using t tests. No significant differences were found. The analysis was therefore performed on the pooled data from both left and right sides. Two different testing procedures were used.

To compare the effect of the afferents from the RA, EO and IO muscles on the motoneurone pool of the ipsilateral and contralateral RA, EO and IO muscles, a one way ANOVA was applied. When this showed a significant difference post hoc testing using Tukey's test was undertaken to investigate which reflexes are the most potent. Secondly, the effect of the afferents from each muscle on the ipsilateral and contralateral homologous muscles was compared using a paired t test.

Prior to applying the tests, the homogeneity of the variances of the data was compared using a Levene test. This calculates the variance of the reflexes and compares whether this variation for the mean amplitude of each reflex is homogenous. If this was not the case then the data was transformed to reduce the variance across the different reflexes. In fact, the only data for which the variances were homogenous was the iRA.
Transforming the data logarithmically resulted in homogenous variation between the
different reflexes to iIO, crIO, and crEO. For both iEO and crRA transforming
logarithmically did not achieve homogeneity of variances. The reflexes to these two
muscles were therefore tested using parametric statistics on transformed data, and non-
transformed data, as well as using non-parametric tests (Kruskal Wallis and Mann
Whitney U tests). For both crRA and iEO all tests gave the same result and the
significance value reported in the following tables is from the parametric tests using
non-transformed data.

The effectiveness of the afferents from RA, EO and IO muscles onto the motoneurones
of RA, EO and IO muscles are arranged on the following pages by the muscle in which
the reflexes were evoked. On each page the following diagrams are shown

- one figure comparing the relative strength of the afferents from RA, EO and IO onto
  that particular muscle. If one afferent is more potent than another this is indicated
  by a red arrow and if there is no difference then a black arrow is used. The p value
  is inserted alongside the arrow and when significant a * is shown. All tests shown
  are post hoc Tukeys test resulting from significant differences revealed using a one
  way ANOVA, except for iRA where no significant difference was detected.

- one bar chart showing the relative amplitudes of the reflexes in each muscle from
  each afferent grouping.

- one table comparing the strength of a group of afferents on the relative ipsilateral
  and contralateral pairs of muscles.
Figure 6.3. Relative effectiveness of rectus abdominis (RA), external oblique (EO) and internal oblique (IO) afferents on ipsilateral RA (iRA) and contralateral RA (crRA) muscles.

<table>
<thead>
<tr>
<th>iRA</th>
<th>crRA</th>
</tr>
</thead>
<tbody>
<tr>
<td>RA afferents</td>
<td>One way ANOVA p=0.435</td>
</tr>
<tr>
<td>EO afferents</td>
<td>p=0.041 *</td>
</tr>
<tr>
<td>IO afferents</td>
<td>p=0.003 *</td>
</tr>
</tbody>
</table>

Table 6.1. Comparison of the amplitude of the reflexes evoked in ipsilateral (iRA) and contralateral (crRA) rectus abdominis (RA) muscles using independent sample t tests. * - Significantly different.

<table>
<thead>
<tr>
<th>Afferents</th>
<th>iRA vs crRA</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>RA</td>
<td>iRA &lt; crRA</td>
<td>0.067</td>
</tr>
<tr>
<td>EO</td>
<td>iRA &gt; crRA</td>
<td>0.039 *</td>
</tr>
<tr>
<td>IO</td>
<td>iRA &gt; crRA</td>
<td>0.314</td>
</tr>
</tbody>
</table>

Figure 6.4. Amplitudes of the reflexes in both the ipsilateral and contralateral RA muscles when tapping on the RA, EO and IO muscles. The data shown is the arithmetic mean of all reflexes and includes those results where no effect was seen.
Figure 6.5. Relative effectiveness of rectus abdominis (RA), external oblique (EO) and internal oblique (IO) afferents on ipsilateral (iEO) and contralateral EO (crEO) muscles.

<table>
<thead>
<tr>
<th></th>
<th>iEO</th>
<th>crEO</th>
</tr>
</thead>
<tbody>
<tr>
<td>RA afferents</td>
<td></td>
<td></td>
</tr>
<tr>
<td>EO afferents</td>
<td>P&lt; 0.001</td>
<td>P&lt; 0.001</td>
</tr>
<tr>
<td>IO afferents</td>
<td>P= 0.841</td>
<td>P= 0.021</td>
</tr>
</tbody>
</table>

Figure 6.6. Amplitude of the reflexes in both the ipsilateral (iEO) and contralateral (crEO) external oblique muscles when tapping the RA, EO and IO muscles. The values shown are the geometric means of the logarithmically transformed data of all reflexes and includes those results where no effect was seen.

<table>
<thead>
<tr>
<th></th>
<th>iEO v crEO –NS</th>
<th>P=0.734</th>
</tr>
</thead>
<tbody>
<tr>
<td>RA afferents</td>
<td>iEO &gt; crEO</td>
<td>P&lt;0.001*</td>
</tr>
<tr>
<td>EO afferents</td>
<td>iEO v crEO –NS</td>
<td>P=0.144</td>
</tr>
</tbody>
</table>

Table 6.2. Comparison of the amplitudes of the reflexes evoked in the ipsilateral (iEO) and contralateral (crEO) external oblique muscle pairs, using independent sample t tests. * - significantly different
Figure 6.7. Relative effectiveness of rectus abdominis (RA), external oblique (EO) and internal oblique (IO) afferents on ipsilateral (iIO) and contralateral IO (cRIIO) muscles.

<table>
<thead>
<tr>
<th></th>
<th>iIO</th>
<th>cRIIO</th>
</tr>
</thead>
<tbody>
<tr>
<td>RA afferents</td>
<td>$P &lt; 0.001^*$</td>
<td>$P &lt; 0.001^*$</td>
</tr>
<tr>
<td>EO afferents</td>
<td>$P &lt; 0.001^*$</td>
<td>$P = 0.024^*$</td>
</tr>
<tr>
<td>IO afferents</td>
<td>$P &lt; 0.001^*$</td>
<td>$P = 0.001^*$</td>
</tr>
</tbody>
</table>

Figure 6.8. Amplitudes of the reflexes in both the ipsilateral (iIO) and contralateral (cRIIO) internal oblique muscles when tapping the RA, EO and IO muscles. The data shown is the geometric mean of the logarithmically transformed data.

<table>
<thead>
<tr>
<th></th>
<th>iIO v cRIIO -NS</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>RA afferents</td>
<td>iIO v cRIIO -NS</td>
<td>P=0.983</td>
</tr>
<tr>
<td>EO afferents</td>
<td>iIO v cRIIO -NS</td>
<td>P=0.059</td>
</tr>
<tr>
<td>IO afferents</td>
<td>iIO v cRIIO -NS</td>
<td>P=0.122</td>
</tr>
</tbody>
</table>

Table 6.3. Comparison of the amplitudes of the reflexes evoked in the ipsilateral (iIO) and contralateral (cRIIO) internal oblique muscle pairs, using independent sample t tests.
6.4 Comparison of the effects of the afferents from RA, EO and IO onto the RA, EO and IO muscles.

A review of the literature did not lead to any hypotheses regarding different potency of the muscle afferents of RA, EO or IO. It is however obvious from the data that there are differences between the effects of the different muscle afferents onto different motoneurone pools (figure 6.9). The wide variation in the data makes comparisons of different pathways from one group of afferents to six different muscles more problematic. However, the reported effects of each group of muscle afferents to ipsilateral and contralateral RA and IO muscles show no significant difference between the two sides. It is therefore possible to pool the ipsilateral and contralateral data to allow comparison of the effect of RA and IO afferents to RA, EO and IO muscles. Comparing the data in this way shows contrasting results between the afferents from IO and RA. The RA afferents showed no significant difference in the amplitudes of the responses to RA, EO or IO (one way ANOVA, p=0.688). In contrast, the effect of IO afferents on the different muscles showed reflexes of significantly greater amplitude in IO than EO and in EO greater than RA (one way ANOVA p<0.001, confirmed on post hoc testing using Tukey’s test).

Analysis of the effects of EO afferents is more complex. This is because the size of the reflexes in the iEO and crEO were significantly different and therefore these could not reasonably be pooled. Therefore, all six muscles were compared using the data when transformed logarithmically. The amplitude of the homonymous reflex in EO was significantly larger than any other reflex evoked by EO afferents. Secondly the responses in both ipsilateral and contralateral RA muscles were significantly weaker than those in all the heteronymous oblique muscles (crEO, iIO and crIO).
Figure 6.9. Amplitudes of the short latency excitatory reflexes between the rectus abdominis (RA), external oblique (EO) and internal oblique (IO) muscles when tapping each muscle as indicated. The data presented is the geometric mean of the logarithmically transformed data.

In summary each group of afferents and muscles can be compared as follows.

- RA afferents evoke reflexes of comparable amplitude to all muscles. RA muscles exhibit reflexes of comparable amplitude from IO and RA afferents, but the reflexes from afferents in the crEO are significantly smaller.

- EO afferents are most potent homonymously and have their weakest connections to both RA muscles especially crRA. The amplitude of reflexes in the EO muscle are comparable from iEO and both iIO and crIO, but the amplitude of the reflexes evoked in and from the RA are weak.
• IO afferents evoke reflexes of comparable amplitude in both ipsilateral and contralateral homologous muscles. They are most potent to IO then to EO and are weakest to RA. The amplitude of reflexes in the IO muscles are comparable when evoked from afferents in RA, EO and IO on either side. However the reflexes in IO when evoked from IO afferents are the largest and those in RA are the smallest reflexes evoked from IO afferents.

6.5 Comparison of the latencies of short latency homonymous and heteronymous responses between the abdominal muscles.

The latencies of the 18 short latency excitatory reflexes between the abdominal muscles occur between 14.7ms and 22.0ms and this is illustrated in figure 6.10. The longest difference in latency of any heteronymous reflex in relation to the homonymous response for those particular afferents is 4.9ms (EO to crEO). The homonymous reflexes are accepted as being spinally mediated. Therefore this difference is too short a time for the heteronymous reflexes to be anything other than spinally mediated.
Figure 6.10. Latencies of homonymous and heteronymous short latency reflexes between the abdominal oblique muscles. Rectus abdominis – RA, external oblique – EO, internal oblique – IO, i – ipsilateral and cr – contralateral.

6.5.1 Predicting the latencies of heteronymous reflexes.

The conduction velocities of the homonymous reflexes in the RA, EO and IO muscles have been estimated by comparing the known latencies to measurements of the conduction pathways taken from skeletons. From this model the estimated average conduction velocities were similar ranging from 49-52m/s. A model estimating the expected latencies of the remaining 15 heteronymous excitatory reflexes between the abdominal muscles has been created by making certain assumptions about these reflex pathways, and this is shown in table 6.4.
Table 6.4. Components of a predictive model of the latencies of the heteronymous reflex responses between the abdominal oblique muscles. From the measured latency 1ms is subtracted to allow for the monosynaptic transmission time between the afferent and the motoneurone pool, and 1ms is subtracted for transmission across the neuromuscular junction. The second assumption made is that the conduction velocities of the afferent and efferent fibres for each muscle are the same, so allowing the remaining time to be divided by two. From this the latency of each heteronymous pathway can be predicted by adding the relevant afferent and efferent times from each of the three pathways and adding on the 1ms central delay and 1ms delay at the neuromuscular junction subtracted from the homonymous response. (See text for details)

<table>
<thead>
<tr>
<th>Homonymous reflex pathway</th>
<th>Latency</th>
<th>Latency minus monosynaptic central delay (1ms) and neuromuscular junction delay (1ms)</th>
<th>Resultant afferent and/or efferent conduction time</th>
</tr>
</thead>
<tbody>
<tr>
<td>RA to RA</td>
<td>20.2</td>
<td>18.2</td>
<td>9.10</td>
</tr>
<tr>
<td>EO to EO</td>
<td>14.7</td>
<td>12.7</td>
<td>6.35</td>
</tr>
<tr>
<td>IO to IO</td>
<td>15.9</td>
<td>13.9</td>
<td>6.95</td>
</tr>
</tbody>
</table>

The first assumption made is that each homonymous response has a monosynaptic component and that the initial latency reflects this connection. This would therefore account for approximately 1ms central delay allowing for transmission across the synapse. In addition, the delay across the neuromuscular junction is likely to be 1ms. A further assumption can then be made that the afferent and efferent conduction velocities are the same for each of the homonymous reflexes. Therefore, the latency remaining after subtracting the monosynaptic and neuromuscular junction transmission times is divided by two. The resultant time is the average for each afferent and efferent pathway and these calculations are shown in table 6.5. The relevant afferent and efferent times for each pathway plus the central and peripheral delays are then summed to produce a predicted onset latency (i.e. IO to EO = 6.9 + 6.35 + 2 = 15.3ms). Each predicted
latency is then subtracted from the actual latency of either the ipsilateral or contralateral response. These differences between actual and predicted latencies are shown in figure 6.11 and table 6.5. These calculations result in more time than would be predicted for the heteronymous reflexes to both the EO and IO muscles. These are appropriate, as the heteronymous pathways will require extra transmission time for two reasons. For the crossed reflexes the afferent connections to the motoneurones will be across the spinal cord. For all ipsilateral and some contralateral heteronymous responses the afferents will need to traverse up or down the spinal cord as the afferents will enter at different segmental levels than the motoneurone pools they are destined to synapse with. Both of these factors are likely to contribute to the difference between the predicted and the actual latency measures involving EO and IO muscles. The situation for the rectus abdominis muscle is however different. Some of the actual latencies of these heteronymous responses are quicker than was predicted, particularly the iEO to iRA reflex.
Figure 6.11. Comparing the predicted and actual latencies of the short latency excitatory heteronymous reflexes between the abdominal muscles. Rectus abdominis – RA, external oblique – EO, internal oblique – IO, i – ipsilateral and cr – contralateral.

<table>
<thead>
<tr>
<th>Species of muscle in which the reflex is evoked</th>
<th>Tap RA muscle</th>
<th>Tap EO muscle</th>
<th>Tap IO muscles</th>
</tr>
</thead>
<tbody>
<tr>
<td>iRA</td>
<td>0.0</td>
<td>-2.0</td>
<td>-1.4</td>
</tr>
<tr>
<td>crRA</td>
<td>1.9</td>
<td>2.1</td>
<td>-0.6</td>
</tr>
<tr>
<td>iEO</td>
<td>0.9</td>
<td>0.0</td>
<td>1.3</td>
</tr>
<tr>
<td>crEO</td>
<td>3.2</td>
<td>4.8</td>
<td>3.2</td>
</tr>
<tr>
<td>iIO</td>
<td>1.5</td>
<td>2.6</td>
<td>0.0</td>
</tr>
<tr>
<td>crIO</td>
<td>1.9</td>
<td>4.3</td>
<td>1.5</td>
</tr>
</tbody>
</table>

Table 6.5. Actual minus predicted latencies of the reflexes between the abdominal muscles. The values shown are those for each reflex involving rectus abdominis (RA), external oblique (EO) and internal oblique (IO) muscle afferents and ipsilaterally or contralaterally positioned muscles.
7 RESULTS 4 -
SHORT LATENCY REFLEX ACTIVITY BETWEEN THE PARASPINAL MUSCLES.

7.1 Short latency ipsilateral excitatory reflexes within and between the LM and IC muscles.

7.1.1 LM homonymous stretch reflex.
A short latency reflex was evoked in the LM in all muscles tested (36/36) with an amplitude of 293±28% (Figure 7.1). In the majority of subjects a clear average response could only be evoked with the subject standing and leaning slightly forward.

7.1.2 IC homonymous stretch reflex.
A short latency reflex was observed in the IC less frequently and was of smaller amplitude than in the LM. The reflex was present 89% of the time (16 of 18 experiments) with an amplitude of 197±29% (figure 7.1).
Figure 7.1. Short latency reflexes in the lumbar multifidus (LM) and iliocostalis lumborum (IC). The points tapped on the LM (upper illustration) and IC (lower illustration) are shown with an X, and the position of the electrodes as pairs of black dots. The middle traces are the average of 30 taps, and 5 individual sweeps of the thirty which make up these averages are shown on the right of the respective average. The tap was applied at the point of the dashed vertical line on the traces.

7.2 Heteronymous reflex connections between the ipsilateral LM and IC muscles.

In addition to the homonymous reflexes evoked in the LM and IC, heteronymous reflexes were evoked in the iIC when tapping the LM (figure 7.2) and in the iLM when tapping the IC (figure 7.3). In fact, these responses occurred in 100% of the experiments undertaken (LM to IC 21 of 21 experiments, and IC to LM 18 of 18 experiments).
Figure 7.2. Short latency excitatory reflexes in the lumbar multifidus (LM) and iliocostalis lumborum (IC) muscles when tapping the LM. The point tapped on the LM is illustrated with an X, and the position of the surface electrodes recording the response in the LM and IC muscles as pairs of black dots. The point at which the tap was applied is indicated by the vertical dashed line.

An example of a short latency excitatory reflex in the IC when tapping LM is shown in figure 7.2. The amplitude of this reflex in IC when tapping LM was on average 212±33%.
Figure 7.3. Short latency excitatory reflexes in the iliocostalis (IC) and lumbar multifidus (LM) muscles in response to tapping the IC muscle in two subjects. The point tapped on the IC muscle is illustrated with an X, and the position of the surface electrodes recording the response in the LM and IC muscles as pairs of black dots. The point at which the tap was applied, is indicated by the vertical dashed line.

An example of a short latency excitatory reflex in LM when tapping IC is shown in figure 7.3. The amplitude of the short latency excitatory heteronymous response in LM in response to tapping the IC was 158±39 % (table 7.1).
<table>
<thead>
<tr>
<th>Point tapped</th>
<th>Tap Lumbar multifidus</th>
<th>Tap Iliocostalis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Muscle Recorded from</td>
<td>Lumbar multifidus</td>
<td>Iliocostalis</td>
</tr>
<tr>
<td>% occurrence</td>
<td>100 (32/32)</td>
<td>100 (21/21)</td>
</tr>
<tr>
<td>Amplitude (% background mean EMG)</td>
<td>293±28</td>
<td>212±33</td>
</tr>
</tbody>
</table>

Table 7.1. Frequency of occurrence and mean amplitudes of the homonymous and heteronymous excitatory reflexes within and between the lumbar multifidus and iliocostalis muscles.
7.3 Reflexes between contralateral paraspinal muscles.

7.3.1 Reflexes connections from LM to the contralateral LM.

In response to tapping the lumbar multifidus muscle the predominant short latency response observed in the crLM was inhibitory. This occurred in 50% of the muscles studied (18/36, figure 7.4). The amplitude of this inhibition is a reduction in the level of background EMG by 63±2%, (table 7.2).

![Figure 7.4](image-url)  
Figure 7.4. Ipsilateral excitatory and contralateral inhibitory short latency reflexes in both lumbar multifidus muscles (LM) to tapping one LM muscle. The point tapped is indicated on the LM by an X, and the position of the surface electrodes are indicated by pairs of black dots on the schematic diagram. The point at which the tap was applied, is indicated by the dashed vertical line on the EMG traces. All responses shown are the rectified then averaged trace of 30 taps.
7.3.2 Reflexes connections from the LM to the contralateral IC.

In response to tapping the ipsilateral lumbar multifidus muscle a short latency inhibitory response was obvious in the crIC muscle 9% of the time (2/22, figure 7.5, table 7.2). The amplitude of the reduction in background EMG was 61±3%.

Figure 7.5. Ipsilateral excitatory and contralateral inhibitory short latency responses in the ipsilateral lumbar multifidus (LM) and contralateral iliocostalis lumborum (IC) muscles respectively, when tapping one lumbar multifidus muscle. The most frequent observation (20/22) is illustrated by subject 1 which shows no effect in the contralateral IC, whilst the effect seen in subject 2 represents the inhibition seen in two of 22 pairs of muscles. The point tapped on the LM is illustrated by an X, and the position of the surface electrodes by pairs of black dots. The point at which the tap was applied, is indicated by the dashed vertical line on the EMG traces. All responses shown are the rectified then averaged trace of 30 taps.
7.3.3 Reflexes connections from IC to the contralateral IC.

In response to tapping the IC muscle on one side a short latency inhibitory reflex was seen in the contralateral IC muscle 11% of the time (2/18, figure 6, table 7.2). However, as can be seen in figure 7.6 even this response (as identified by dropping outside 2SD of the background mean) was of very short duration. In only one further muscle was there any sign of a short latency inhibition. The amplitude of the two reflexes identified was a reduction of the mean pre stimulus EMG activity of 51±7%, (table 7.2).

Figure 7.6. Short latency reflexes in the ipsilateral and contralateral iliocostalis lumborum (IC) muscles respectively, when tapping one IC muscle. The most frequent response (16/18) is illustrated in subject 1 showing no effect in the contralateral IC, whilst the effect seen in subject 2 illustrates the inhibition seen in 2 of 18 subjects. The point tapped on the IC muscle is illustrated by an X, and the position of the surface electrodes by pairs of black dots. The point at which the tap was applied, is indicated by the dashed vertical line on the EMG traces. All responses shown are the averaged rectified trace (30 sweeps).
7.3.4 Reflexes from the IC muscle to the contralateral LM muscle.

In response to tapping the IC muscle a short latency inhibition was observed in 25% of the crLM muscles (5/16, figure7.7, table 7.2). The amplitude of the reduction in mean pre stimulus EMG activity was 54±4%, (table 7.2).

![Figure 7.7. Short latency excitatory and inhibitory reflexes in the ipsilateral iliocostalis lumborum (IC) muscle and the contralateral lumbar multifidus (LM) muscle respectively when tapping one IC muscle, in two subjects. The point tapped on the IC is illustrated by an \( X \), and the position of the surface electrodes by pairs of black dots. The point at which the tap was applied, is indicated by the dashed vertical line on the EMG traces. All responses shown are the averaged rectified traces of 30 sweeps.](image-url)
### Table 7.2. Frequency of occurrence and amplitudes of contralateral inhibitory reflexes between the lumbar multifidus and iliocostalis muscles.

<table>
<thead>
<tr>
<th>Point tapped</th>
<th>Tap Lumbar multifidus</th>
<th>Tap Iliocostalis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Muscle Recorded from</td>
<td>Lumbar multifidus</td>
<td>Iliocostalis</td>
</tr>
<tr>
<td>% occurrence</td>
<td>50 (18/36)</td>
<td>9 (2/22)</td>
</tr>
<tr>
<td>Amplitude (% reduction) ±SEM</td>
<td>63±2</td>
<td>61±3</td>
</tr>
<tr>
<td>Duration of inhibition (ms) ±SEM</td>
<td>11.3±1.3</td>
<td>9.6±3.0</td>
</tr>
</tbody>
</table>

7.4 Comparison of the different inhibitory reflexes between contralaterally positioned paraspinal muscles.

Comparison of the strength of these crossed inhibitory effects can be analysed by either the muscle from which the afferents have come from, or the muscle they affect. The most obvious factor is the greater occurrence of the reflexes seen in the LM muscle compared to that in the IC muscle (50 & 32% v 9 and 11%). Comparing the relative amplitude of the inhibitory pathways in isolation shows remarkable similarities (range 51% to 61%) irrespective of the pathway involved. In summary, the inhibitory reflexes from paraspinal muscle afferents to contralaterally positioned paraspinal muscles are observed more frequently in the LM muscle than in the IC muscle.
7.5 Possible excitatory reflexes in the contralateral paraspinal muscles to tapping the ipsilateral paraspinal muscles.

In addition to the short latency inhibition observed in the contralateral paraspinal muscles, short latency excitatory responses were also observed but less frequently. These effects were predominantly observed in the contralateral LM muscle when tapping the ipsilateral LM, rather than during the other three combinations between the paraspinal muscles. This occurred 33% of the time in 12 pairs of LM muscles (12/36). The average size of the response was 119±19%. The latencies of these contralateral responses ranged between 13.2 and 14.2ms, only just longer than the iLM homonymous reflex. An example of one of the largest of these responses is shown in figure 7.8.

A similar contralateral excitatory reflex has been reported previously by Dimitrijevic et al. (1980) and these authors attributed this effect to vibration from the perturbation on the ipsilateral side spreading and evoking a homonymous response in the contralateral muscle. In order to examine whether the results from the study being reported here could be similarly explained, the spinous process of L2 in five subjects was tapped. Short latency excitatory responses were indeed observed in both LM muscles of all 5 subjects tested (cf; Tani et al. 1997). Given the short distance between the point of tap and the spinous process it may be that these short latency crossed excitatory responses in the LM are induced by vibration spreading across and evoking a homonymous response in the muscle on the other side.
Figure 7.8. An example of short latency excitatory responses in both the ipsilateral and contralateral lumbar multifidus (LM) muscles when tapping on one LM only in one subject. The point tapped on the LM is illustrated by an X, and the position of the surface electrodes are indicated by pairs of black dots. The point at which the tap was applied, is indicated by the dashed vertical line on the EMG traces. The responses shown are the non-rectified average, and the rectified then averaged trace, of 30 taps.

In support of this, only three other short latency responses were seen between the other paraspinal muscles positioned on the left and right sides in 56 experiments, two in IC when tapping LM, and one in LM when tapping IC (table 7.3). Furthermore, no short latency excitation was ever observed in the contralateral IC when tapping the ipsilateral IC (table 7.3). In the light of the sparcity of these excitatory responses, and the likely possibility of the mechanical tap spreading contralaterally it seems likely that the excitatory responses contralaterally are artifactual.
7.6 Overview of reflexes between the lumbar paraspinal muscles.

The traces in figure 7.9 exemplify the overall pattern of muscle afferent connections to and from the LM and IC muscle with excitation ipsilaterally and inhibition contralaterally. However the inhibition occurs less frequently and is focused on the LM muscle.

Figure 7.9. Short latency reflexes in both ipsilateral and contralateral lumbar multifidus and iliocostalis muscles, when tapping one lumbar multifidus muscle (left hand traces), and one iliocostalis muscle (right hand traces). The points tapped on each muscle are illustrated by an X, and the position of the surface electrodes as pairs of black dots. The point at which the tap was applied, is indicated by the dashed vertical line. All responses shown are the rectified averaged traces of 30 sweeps.
7.7 Comparison of the latencies of short latency excitatory and inhibitory reflexes between the LM and IC muscles of both sides.

The latency of the homonymous LM reflex is 11.8±0.2ms, and that for the homonymous IC reflex is 12.3±0.3. The difference between the two is not significant (table 7.4).

7.7.1 Conduction velocity of the nerve fibres mediating the homonymous LM reflex response.

Any estimates of conduction velocity for the axons supplying the LM muscles are more reliable, as there is more certainty regarding the course of the peripheral nerve supplying the muscle. In these estimates, it was assumed that the afferent and efferent conduction velocities are the same. The LM is known to be a segmented muscle originating from the five lumbar vertebrae and that the muscle fibres attaching proximally to a vertebra are supplied by the nerve root exiting from the same vertebral level (Macintosh et al. 1986; Shindo, 1995). The EMG data for the present study was collected over the lateral aspect of the LM, which is supplied from the L1 segment. The motoneurone pool of the LM muscle is positioned at each level of the lumbar spinal cord. The conduction distance of the L1 supplied LM was therefore measured to the L1 spinal cord segment which is estimated to be at the T9 vertebral level (Carpenter, 1985). So, from the LM attachment to L1, to the T9 vertebral level and back to the muscle measured on average 0.50±0.02m on five skeletons. Calculations of the conduction velocity using this distance, the average latency of 11.8ms, and subtracting 1ms each for central monosynaptic delay and for delay at the neuromuscular junction, gives a conduction velocity of 51m/s. The conduction velocity calculated using the fastest measured latency (9.0ms) is 71m/s.
7.7.2 *Conduction velocity of the nerve fibres mediating the IC homonymous reflex response.*

Neither the course of the nerve supply or the position of the motoneurone pool of the IC muscle, have been reported in detail. Therefore, estimates of the conduction velocity of the reflex response within this muscle are less reliable. Firstly, the muscle attaches to the thorax and extends to the pelvis and therefore does not attach to different vertebral levels. Whilst the nerve supply is segmental from L1 to L4 as outlined in the Introduction (section 1.6.3), the exact segmental level which supplies each part of the muscle is uncertain and the level of the motoneurone pool supplying the muscle underlying the surface electrodes is unknown. To this end two assumptions were made; firstly that the peripheral nerve entered and exited via the upper lumbar vertebrae and secondly that the IC motoneurone pool is situated in the upper lumbar spinal cord level with T9. The distance from the position of the EMG over the IC muscle, to the upper lumbar vertebral column, and then to the appropriate vertebral level and back to the muscle, was measured on five skeletons as 0.42±0.1 m. Calculating the conduction velocity using the average latency (12.3 ms) gives a value of 40 m/s. This is lower than for any of the other four muscles measured in this study (mean range 49 m/s – 52 m/s). Of course, it is entirely possible that this muscle has a conduction velocity slower than the other trunk muscles measured. On the other hand it may suggest inaccuracies within the model. As there is no other data upon which to base an estimate of the conduction distance to and from the IC, it may be that the assumptions used are incorrect. The measurement taken of the course of the peripheral nerve to and from the IC muscle was to the upper lumbar spine near L1. It may be that one of the lower segments (L2, L3 or even L4) supplies the muscle at the point recorded from in this study. This would alter the conduction distance. A difference of 30 mm within the periphery would give an
average conduction velocity of 48m/s and a fastest conduction velocity of 60.5m/s, both of which are comparable to the conduction velocities measured from RA, EO, IO and LM. This distance corresponds to that between one or two vertebral levels and would therefore be compatible with the nerve supply of IC at the point recorded from being from L2 or L3.

7.7.3 Latencies of the ipsilateral excitatory and contralateral inhibitory reflexes.

The latency of all four short latency excitatory reflexes within and between the ipsilateral LM and IC muscles were similar (range 11.8 – 12.5ms). In contrast the range of latencies for the contralateral inhibitory reflexes were longer, ranging from 20.9±0.5 to 22.6±1.4ms. These latencies are all shown in figure 7.10 and detailed in table 7.3.

![Figure 7.10](image.png)

Figure 7.10. Mean latencies (±SEM) of both excitatory and inhibitory short latency reflexes within and between the lumbar multifidus (LM) and iliocostalis lumborum (IC) muscles on both sides of the vertebral column.
Table 7.3. Latencies and range of ipsilateral excitatory and contralateral inhibitory reflex latencies between the lumbar multifidus and iliocostalis lumborum muscles.

<table>
<thead>
<tr>
<th></th>
<th>Tap lumbar multifidus</th>
<th>Tap iliocostalis lumborum</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>lumbar multifidus</td>
<td>iliocostalis lumborum</td>
</tr>
<tr>
<td><strong>Ipsilateral Excitation</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Latency mean±SEM (ms)</td>
<td>11.8±0.2</td>
<td>11.2±0.4</td>
</tr>
<tr>
<td>Range (ms)</td>
<td>9.0 – 14.9</td>
<td>9.4 – 15.4</td>
</tr>
<tr>
<td><strong>Contralateral Inhibition</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Latency mean±SEM (ms)</td>
<td>20.9±0.5</td>
<td>22.6±1.4</td>
</tr>
<tr>
<td>Range (ms)</td>
<td>17.5-24.9</td>
<td>19.4 – 25.0</td>
</tr>
</tbody>
</table>
7.8 Analysis of the frequency of occurrence, amplitude and latency of reflexes between the LM and IC muscles.

7.8.1 Frequency of occurrence.

The frequency of occurrence of both ipsilateral and contralateral reflexes between the LM and IC muscles are shown in figure 7.11. The short latency excitatory reflexes between iLM and iIC occur almost invariably. In contrast, the short latency effects on the contralateral side are predominantly inhibitory and occur most often in the LM muscle and in response to activating LM afferents.

![Frequency of occurrence of short latency reflexes between the lumbar multifidus (LM) and iliocostalis lumborum (IC) muscles. i – ipsilateral, cr - contralateral](image)

Figure 7.11.
7.8.2 Amplitude of reflexes in paraspinal muscles.

The relative amplitudes of the short latency excitatory reflexes in the iLM and iIC muscles evoked from LM and IC muscle afferents are highlighted in figure 7.12. Analysis of these by a one way ANOVA reveals a significant difference (p=0.006).

Further analysis of these significant differences was undertaken using post hoc testing (Tukey’s test). This showed significant differences between reflexes evoked by LM and IC afferents. The reflexes from the LM afferents to iLM were of greater amplitude than from IC afferents to IC and iLM (table 7.5).
### Table 7.4

<table>
<thead>
<tr>
<th></th>
<th>Post hoc Tukey's test – p value</th>
</tr>
</thead>
<tbody>
<tr>
<td>LM to LM v LM to IC</td>
<td>0.181</td>
</tr>
<tr>
<td>LM to LM v IC to LM</td>
<td>0.017*</td>
</tr>
<tr>
<td>LM to LM v IC to IC</td>
<td>0.032*</td>
</tr>
<tr>
<td>IC to IC v LM to IC</td>
<td>0.872</td>
</tr>
<tr>
<td>IC to IC v IC to LM</td>
<td>0.991</td>
</tr>
<tr>
<td>LM to IC v IC to LM</td>
<td>0.727</td>
</tr>
</tbody>
</table>

Table 7.4. Comparison of the amplitudes of short latency excitatory reflexes from LM and IC afferents to the ipsilateral LM and IC muscles, using post hoc significance testing. Significant differences are indicated by a *.

### 7.8.3 Comparison of the crossed inhibitory actions of LM and IC afferents.

The differences in amplitudes of the inhibitory responses to crLM and crIC muscles were revealed using one way ANOVA testing. A post hoc Tukeys test revealed the short latency inhibitory effect in crLM from iLM to be significantly greater than the inhibitory reflex in IC from either group of muscle afferents.
7.9 Comparison of latencies of ipsilateral excitatory and contralateral inhibitory reflexes in the lumbar paraspinal muscles.

Comparison of the latencies of the ipsilateral short latency excitatory reflexes in LM and IC were analysed using a one way ANOVA and found not to be significantly different (p=0.146). Comparison of the latencies of the contralateral short latency inhibitory reflexes in the LM and IC muscles to tapping the LM and IC muscles ipsilaterally were also found not to be significantly different using a one way ANOVA (p=0.163). To allow comparison of the ipsilateral and contralateral effects all the ipsilateral excitatory latencies were pooled, as were all the contralateral inhibitory latencies. An independent sample t-test was then performed and the ipsilateral excitatory reflexes were found to occur significantly earlier than the contralateral inhibitory reflexes (p<0.001). Using the same data the ipsilateral excitation was found to occur on average 9.1ms earlier than the crossed inhibition.
7.10 Summary of short latency excitatory reflexes between the LM and IC muscles on both sides.

Short latency excitatory homonymous and heteronymous reflexes were evoked in both the LM and IC muscles by use of a mechanical tapping device. Homonymous reflexes were evoked in the LM muscle in all experiments (36/36) but a homonymous short latency reflex was evoked in only 16 of 18 IC muscles tapped. Short latency heteronymous excitatory reflexes were evoked in the ipsilateral IC from LM afferents and the ipsilateral LM from IC afferents in 100% of experiments. In contrast to the connectivity between the contralateral abdominal muscles, minimal contralateral excitatory activity was seen. The predominant effect seen in the contralateral muscles was a short latency inhibition, most commonly in the LM muscle.

The latencies of these responses were compared with the conduction distance as measured on five skeletons. The estimated conduction velocities of nerve fibres mediating these reflexes confirm that these responses are spinoally mediated. The latencies of all the ipsilateral excitatory reflexes were comparable, as are all the contralateral inhibitory reflexes. However, the latency of the crossed inhibition in both LM and IC muscles is on average between 8 and 10ms longer than the ipsilateral reflexes.

The main difference between the contralateral reflexes within the abdominal and paraspinal muscle groups is that the abdominal reflexes are excitatory, whereas the contralateral reflexes between the paraspinal muscles are inhibitory.
8 RESULTS 5 -
SHORT LATENCY REFLEXES BETWEEN THE IO AND LM MUSCLES.

Possible reflex connections between the IO and LM muscles were also investigated by evoking activity in the IO and LM muscles whilst recording activity in the muscle group on the opposite aspect of the trunk, (IO to LM and LM to IO).

8.1 Short latency reflexes from the IO to the LM muscles.

To investigate any possible short latency reflexes in the LM from afferents within the IO muscle, the IO tendon was tapped medial and adjacent to the ipsilateral ASIS. A short latency reflex was evoked in the ipsilateral LM on 41% of occasions (7/17 experiments, in 9 subjects). However, it was also noted that a short latency excitatory response was produced in the same LM muscle when tapping on the ipsilateral ASIS in 64% of experiments (11/17, paired data, figure 8.1). This effect may therefore be produced by the perturbation on the ASIS vibrating the iliac bone to which part of the LM attaches posteriorly so evoked activity in LM afferents.

In addition, the latency of these responses in the iLM muscle when tapping both on and medial to the ipsilateral ASIS are comparable to the latencies of the homonymous response in the same LM muscle. Any possible heteronymous reflex from IO to LM would necessarily involve afferents from the IO muscle. The latencies of the homonymous IO reflex are on average 4ms longer than the homonymous LM responses, as is the measured conduction distance. Therefore, any heteronymous reflex from IO to LM should be longer than the homonymous LM reflex as the overall conduction distance from IO to LM is longer than from LM to LM. As the latency of the responses
observed in LM when tapping a) the LM, b) medial to the ASIS and c) on the ASIS are similar, this may indicate that these responses are all evoked homonymously.

![Diagram of short latency reflexes in the lumbar multifidus in response to tapping three different points on the anterior aspect of the abdomen; medial to the ASIS, on the ASIS and in the midline below the umbilicus in one subject. As can be seen there are obvious short latency responses in the muscle when tapping medial and adjacent to the ASIS and on the ASIS but not when tapping the anterior abdomen away from bone.](image)

**Figure 8.1.** Short latency reflexes in the lumbar multifidus in response to tapping three different points on the anterior aspect of the abdomen; medial to the ASIS, on the ASIS and in the midline below the umbilicus in one subject. As can be seen there are obvious short latency responses in the muscle when tapping medial and adjacent to the ASIS and on the ASIS but not when tapping the anterior abdomen away from bone.

Muscle afferent activity from within the IO was therefore evoked by tapping the anterior abdomen below the umbilicus in the midline, so avoiding the vibration evoked from tapping on or near the ASIS (figure 8.1 & 8.2). One further effect of this midline tapping is that any reflexes in both LM muscles would be as a result of the same tension...
generated in both IO muscles. Consequently, both LM muscles could be investigated simultaneously and therefore the effects in 30 LM muscles in 15 subjects were studied.

The predominant result when tapping the anterior abdomen and recording from LM was neither excitation nor inhibition as illustrated in figures 8.1 & 8.2. In fact there was no response in 23 of the 28 muscles studied (82%).

![Diagram of muscles](image)

**Figure 8.2.** Excitatory short latency reflexes in the internal oblique muscles with no short latency reflexes in the lumbar multifidus muscles when tapping the anterior abdomen in one subject. The point tapped is illustrated as an X and the position of the surface electrodes as pairs of black dots.

Of the five reflexes identified, they all showed some excitation and one showed both excitation and inhibition. The excitatory reflexes observed were weak being only just greater than 2SD from the background mean. In three of the five responses seen, the effect was only apparent on the rectified trace. As latency has been measured thus far in this study using non-rectified data, the lack of an obvious reflex in these three muscles
without rectification makes the measurement of latency in this case difficult. In order to identify whether the responses were of short latency, measurements from these responses were taken when possible from the non-rectified traces and in the other three from the rectified trace. These reflex latencies ranged from 12.9 to 23ms. In summary, the effects seen within the LM muscle in response to tapping the IO muscle in the midline occurred on less than 20% of occasions tested and were unimpressive. These results are not convincing evidence to support existence of effective reflexes. On the other hand it was clear from the response evoked in IO that IO afferents were effectively activated. It follows that the unimpressive reflexes observed in the LM reflect the lack of reflex connections between these muscles rather than an inability to detect them.

8.2 Short latency reflexes from the LM to the IO muscles.

In response to tapping the LM muscle the predominant effect seen in both iIO and crIO muscles at short latency was no change in the background mean EMG level. In only 26% of experiments (9/34) was an excitatory response observed in the iIO and in 29% of experiments (10/34) in the crIO muscle (figure 8.3). No short latency inhibitory effects from LM to IO were noted. The amplitudes of the short latency excitatory reflexes in iIO was 152±35% and that in crIO was 90±8% (table 8.1). It is worth noting that the amplitudes of these reflexes are less than 20% of both the iIO and crIO reflexes when tapping the IO muscle.
Figure 8.3. Short latency excitatory reflexes in the lumbar multifidus muscle (LM) and both internal oblique muscles (IO) to tapping on the LM muscle in one subject. The point tapped is illustrated by an X, and the electrode positions as pairs of black dots.

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Table 8.1. Frequency of occurrence and amplitudes of short latency reflexes in the IO muscles to tapping the lumbar multifidus.
It is worth pointing out at this stage that the IO muscle has been noted to attach to the upper lumbar vertebrae via the posterior layer of the thoraco-lumbar fascia, in one cadaver of 10 studied (Bogduk & Macintosh, 1984). It is at this point in the upper lumbar spine that the tap on the LM was applied. The tap may therefore have evoked the reflex in the IO on the same side homonymously by this posterior attachment of IO and via the same IO afferent activity in the crlO. However, in four experiments when tapping the LM a reflex was apparent in crlO but not rIO. This reflex in crlO cannot originate from IO afferent activity.

In summary, the infrequent occurrence of these responses in the IO muscles to tapping over LM, as well as the fact that they are less than 20% of the size of the homonymous responses in the IO muscles does not indicate an effective reflex. In addition, the possibility that the proximal attachment of the IO muscle may also be stretched in some subjects by its connection to the thoraco-lumbar fascia that overlies the LM muscle, may indicate that some of these reflexes seen in rIO are homonymous in nature. The uncertainty as to the possible mechanism by which reflexes are evoked, combined with the low frequency of occurrence and small amplitude of the responses, suggest that if they do exist they are not very effective.

8.3 Comparison of the frequency of occurrence and amplitudes of the short latency reflexes between the IO and LM muscles.

The frequency of occurrence, and amplitudes of the reflexes between IO and LM are presented in figures 8.4 & 8.5 for comparison.
Figure 8.4. Frequency of occurrence of short latency reflexes between the internal oblique (IO) and lumbar multifidus (LM) muscles. i – ipsilateral, cr - contralateral

Figure 8.5. Amplitudes of the short latency reflexes between the internal oblique (IO) and lumbar multifidus (LM) muscles. i – ipsilateral, cr - contralateral
8.4 Summary of short latency excitatory reflexes between the LM and the IO muscles.

Due to the proposed role of both of IO and LM in stabilising the trunk, any short latency reflexes between them were investigated using the mechanical tapping device as previously described for all abdominal and paraspinal muscles. The tap on IO was applied in the midline anteriorly, whilst the LM was tapped at it’s proximal end. Any reflexes observed were excitatory and weak from both IO to LM and LM to IO. In addition, there was no short latency inhibition of note in either direction.
8.5 Summary of short latency reflexes within and between the abdominal and paraspinal muscle groups.

When comparing the results of all the investigations of reflexes in the six abdominal and four paraspinal muscles a pattern emerges.

- The most prolific and potent interactions are between the EO and IO muscles of both sides. This is especially evident between the left and right IO muscles.

- Those reflexes involving the RA muscle are less frequently seen and probably less effective. They are however still wide ranging and involve both ipsilateral and contralateral muscles.

- In contrast, the pathways between the paraspinal muscles are excitatory ipsilaterally and predominantly inhibitory or lacking, to the contralateral muscles.

- Finally, reflex interactions between the internal oblique and lumbar multifidus muscles on opposite aspects of the trunk are infrequent, weak and when present only excitatory.
9 DISCUSSION 1 -
SHORT LATENCY REFLEXES BETWEEN HUMAN TRUNK MUSCLES.

9.1 Methodological considerations.

9.1.1 The afferent volley produced by a mechanical tap to muscle and the reflex connections made with motoneurones by this volley.

Tapping a muscle or tendon is thought to predominantly evoke activity in Ia muscle afferent fibres and as the tap is applied through skin activity in cutaneous afferents is also likely. It is also possible that such a tap may evoke activity in group II muscle afferents (Burke et al., 1983). However group II afferent endings are more sensitive to a change in length rather than the velocity of that change appreciated by Ia afferents. In addition group Ib afferents may form part of the volley however they are mainly thought to respond to changes in tension within the tendon produced by contraction of the muscle, rather than a change in length (Houk & Henneman, 1967). The balance of evidence indicates therefore, that short latency reflexes evoked by the application of a tap to a muscle, or tendon, are evoked by group Ia afferents, which are sensitive to both change in length of muscle spindles and the velocity of that change. There may however, be some involvement of cutaneous afferents in evoking the response. In addition whilst it is known that Ia muscle afferents form monosynaptic connections with motoneurones, oligosynaptic and polysynaptic pathways may also contribute to the reflex responses evoked (Burke et al 1984, for full discussion see below).
The results presented here demonstrate that tapping individual trunk muscles produces short latency excitatory reflexes in not only the same muscle but also other trunk muscles. Thus there is widespread connectivity of the muscle afferents from the muscle being tapped, to the motoneurone pools of different muscles. Heteronymous reflexes between human arm muscles have also been demonstrated using a similar technique (McClelland et al. 2001).

9.1.2 Possible consequences of the tap having a direct mechanical action on remote muscles.

Teasdall & van Den (1982) have previously reported responses in RA and EO muscles when tapping the RA and EO muscles on the opposite side. These authors concluded that the responses in the distant muscles were produced by a spread of vibration from the application of the tap, evoking the responses homonymously. In addition Lance & De Gail, (1965) using a brisk tap to the tendon in the lower leg evoked reflex responses in the muscles of the thigh. The latency of this response was too short to be mediated via the afferents from the muscles tapped below the knee. The authors therefore concluded that these responses were evoked via afferents in the muscles of the thigh by the vibration from the tap applied below the knee. However, various pieces of evidence suggest that the reflexes observed between the abdominal muscles in this report were evoked heteronymously.

Firstly, differences in the latencies of the reflexes evoked in the RA muscle when tapping at different points highlight the heteronymous nature of the response from the EO and IO muscles to RA (figure 9.1). If tapping on the EO or IO muscles does produce a direct mechanical effect in RA, and this evokes RA afferent activity, the
Figure 9.1. Shorter latencies of reflexes from external oblique (EO) and internal oblique (IO) muscle afferents to rectus abdominis (RA) than from RA afferents to RA. a) the homonymous RA and the ipsilateral EO to RA reflex latencies and b) homonymous RA and ipsilateral IO to RA reflex latencies. The EO and IO afferent evoked reflexes in RA are in both instances of shorter latency than tapping on RA. This confirms that the reflex is not generated by direct mechanical action spreading to RA. If that were the case then the latency of the RA reflex would be at the very least of equal latency to that in EO and IO, whereas the latency of the RA homonymous reflex is in fact later. The point tapped and the muscle recorded from are illustrated as an X, and pairs of black dots respectively.
latency of the reflex in iRA could never be shorter than the homonymous iRA reflex. In fact the latencies of the reflexes in iRA when tapping on the EO and IO muscles are significantly shorter than when tapping on RA directly (p<0.01 for both comparisons, figure 6.10). This demonstrates that the reflexes in RA when tapping on EO and IO cannot be produced by direct mechanical action evoking RA afferent activity. Therefore, these reflexes must be generated from afferents in the EO and IO muscles tapped which have shorter peripheral conduction distances than the RA afferents. This is confirmed statistically since both the EO to RA and IO to RA latencies are significantly shorter than that from iRA to iRA (p<0.01 for both comparisons)

Secondly the abdominal wall was tapped at three points a, b & c as illustrated in figure 9.2.

Figure 9.2. Confirmation that the reflex in contralateral EO when tapping the ipsilateral EO is spinally mediated. Data from the EO muscle under the surface electrodes when tapping a) the ipsilateral EO, b) the midline below the ziphistemum away from the EO tendon, and c) over the contralateral EO muscle are illustrated. There is an obvious reflex when tapping both ipsilateral and contralateral EO muscles, but not when tapping point b, which is closer to the EO muscle than the tap on the contralateral EO. This therefore demonstrates that the reflex evoked in EO when tapping the contralateral EO muscle is unlikely to be mediated via a wave of vibration across the abdomen. All data are the average of 30 sweeps.
Point a) and c) are directly on the EO muscle belly ipsilateral and contralateral to the electrodes respectively and both evoke a reflex in the same EO muscle. To demonstrate that the EO reflex when tapping at point c) is not generated by vibration across the abdominal wall evoking a homonymous EO reflex, a series of taps were also applied at point b) in the midline (illustrated in figure 9.2). This is nearer to the muscle recorded from than point c), and yet no response is apparent. Therefore, tapping on one EO muscle produces a response in the opposite EO muscle but tapping closer to the muscle recorded from does not. This demonstrates that the reflex in EO is due to reflex pathway across the spinal cord, and not vibration spreading across to evoke a homonymous reflex in EO. This effect is confirmed by the infrequent occurrence of short latency reflexes in the EO muscles when tapping directly on the RA rather than in the midline. In addition, a response in the crRA when tapping the iEO muscle was only seen in two of eleven experiments, whereas the short latency response in the more distant crEO when tapping iEO afferents occurred in 18 of 22 experiments. These findings indicate that the responses in crEO are heteronymously evoked and are not as a result of vibration from the tap spreading to adjacent muscles and evoking a homonymous response.

To investigate whether vibration from the application of the tapper across the abdominal wall caused a reflex in crIO homonymously when tapping on iIO, two experiments were undertaken. Firstly, an accelerometer was positioned just above the recording electrodes over the IO muscle. The tap was then applied medial to the ASIS on the same side and also on the contralateral side. This is illustrated in figure 9.3 and shows clearly that the degree of vibration reaching the surface on the contralateral side is much reduced. Whilst this may not reflect the exact degree of vibration in the underlying
Figure 9.3. Displacement of the tissue at the EMG recording site over the left internal oblique muscle (IO), when tapping the IO on the left and right sides. Taps were applied at each X on the illustration, and the displacement was detected by the accelerometer represented by the black dot illustrated. The displacement shown is represented on the y axis on each trace, and the tap was applied at the vertical dashed line in both traces. The displacement of the tissue is much reduced on the muscle contralateral to the tap.

muscles, it is an indication of the reduction in amplitude of the vibration when reaching the opposite side. In addition, even if some vibration does reach the crIO afferents, the amplitude of the displacement created will be much reduced. The size of a stretch reflex in the abdominal muscles has been shown to be correlated with the amplitude of the tap producing it (Kondo et al. 1986) and therefore a smaller displacement would produce a reflex of much reduced amplitude. This was clearly not the case in this study as the crIO reflex was of comparable amplitude to that in ilO.

Secondly, a series of taps were applied on the ASIS and on the IO tendon/muscle medial to the ASIS, whilst recording the responses in left and right IO muscles. It might be expected that tapping on the rigid bone would set up vibration of greater amplitude than when tapping the soft tissue on IO (the more compliant soft tissue is
likely to attenuate the vibration). The level of displacement of the tap on the ASIS was set at just below threshold for inducing a reflex in the adjacent iIO muscle. If the crossed reflex is induced by vibration then it would not be expected to be apparent when tapping on soft tissue medial to the ASIS with the same level of force. As illustrated in figure 9.4 the crossed reflex was only apparent when tapping the IO tendon and not on the bone (ASIS).

Figure 9.4. Reflexes evoked in both internal oblique muscles when tapping on adjacent bone and on the IO muscle. The anterior superior iliac spine (ASIS) was tapped in a) and the IO tendon was tapped in b). The amplitude of the tap was the same for both experiments and was set at just below threshold for inducing a reflex in the ipsilateral IO muscle, when tapping on the ASIS. The traces when tapping on the IO muscle show obvious reflexes in both ipsilateral and crossed IO muscles, but not so when tapping on the ASIS. The contralateral IO response is therefore unlikely to be evoked by vibration across the abdomen. The tap was applied at the beginning of the trace.

Assuming that a tap on bone does produces a greater wave of vibration than tapping on compliant soft tissue, this result shows that the crossed reflex is unlikely to be generated by vibration of remote tissues. It also indicates that the short latency reflexes are more
likely to be evoked by muscles afferents being stretched rather than cutaneous afferents which are most probably evoked to the same degree by taps of equal amplitude. Thus, this final control experiment demonstrates that the afferents most likely to be producing the crIO reflex are, i) situated in the muscle and not the skin, and ii) situated in the ipsilateral rather than the contralateral IO muscle. In conclusion, the four pieces of evidence presented indicate that the reflexes identified in the abdominal muscles when tapping on one particular abdominal muscle are best explained as heteronymous reflexes via reflex connections within the spinal cord.

9.1.3 The possible effect of pulling on the conjoint tendon across the anterior abdomen.

As detailed in the introduction the abdominal oblique muscles are attached across the abdomen anteriorly. Kondo et al. (1986) suggested that application of a tap on the EO and IO muscles may produce tension in the conjoint tendon which pulls on the muscles contralaterally, so evoking a homonymous reflex in these contralateral muscles. If so, then the reflex in the crIO might be produced in this way. However, two factors would seem to counter this suggestion.

Both Askar (1977) and Rizk (1980) state that the tendons of EO and IO are sinuous in nature as they cross the midline anteriorly. This arrangement is thought to be necessary to allow subjects to breathe with less resistance, as taut tendons would prevent the increase in diameter of the abdomen needed during respiration. This slack would need to be taken up by any pull on the tendon contralaterally before a substantial and similar change in muscle length was produced on the opposite side. Moreover, as already
stated such a perturbation would need to be of a magnitude equal to that created ipsilaterally, in order to produce a reflex of the same amplitude.

Secondly, real time ultrasound imaging equipment was used to observe any movement of the conjoint tendon joining the muscles of either side. Subjects were asked to hollow their stomach, an activity which is known to activate the IO muscle (Beith et al. 2001). During this manoeuvre the tendons were imaged with the real-time ultrasound, and they were observed to move on the image, so demonstrating that movement in the tendons can be observed using this technique. The conjoint tendon was then imaged in two further situations. Firstly, a mechanical tap was applied to the tendon medial to the ASIS using a reflex hammer. Here a small degree of movement was observed within the tendons, although the degree of movement was much reduced from that seen during the hollowing. Secondly, the mechanical tap was applied as in the protocol for this study, and in this instance no movement of the tendon across the anterior abdomen was observed. This suggests that any pull on the contralateral tendon from the tap applied in this study if present at all is minimal. As has already been stated a pull of such reduced magnitude would not produce reflexes of comparable size in both the iIO and crIO muscles. These two pieces of evidence also support the hypothesis that the contralateral responses are produced via heteronymous pathways from afferents of the muscle tapped crossing the spinal cord and not via a pull on the conjoint tendon large enough to evoke substantial afferent activity from the crIO muscle.
9.1.4 Confirmation of the muscle of origin of the EMG signal.

One further technical point to be addressed is how specific the EMG signal recorded is to one muscle. Firstly, it may be that the EMG activity being detected medial to the ASIS is from TrA, rather than IO. This is important as the crossed TrA is connected to the iLO and might therefore be expected to be closely coupled. Fuglevand et al. (1992) have devised a model, incorporating real EMG data, estimating the proportion of EMG activity contributing to the compound signal detected by surface electrodes at different depths. This model assumes that the recording electrodes are positioned 20mm apart, as was the case in the present study. This suggests that 90% of the signal would be detected from the tissue closer than 11-12mm from the surface. Ultrasound images were recorded of the depth of the IO and TrA muscles at the recording site medial to the ASIS on two subjects. These show the most superficial part of the TrA to be deeper than 11-12mm (figure 9.5). This indicates that the vast majority of the ongoing EMG signal detected at these recording sites is from the more superficial IO muscle.

However the extent of cross talk between different muscles may be greater when interpreting synchronised averaged reflex data, such as that measured within this study, as opposed to that from ongoing EMG. If a more extensive spread of cross talk does contribute to some of the average waveforms seen then the signal detected over EO and the underlying IO on the lateral abdominal wall may reflect activity from both muscles. In contrast however, it has been shown that surface recording electrodes detect signals most effectively when arranged in parallel with the direction of the muscle fibres. At the point where the EO signal is detected the direction of the IO muscle fibres deep to the EO are at 90° to those of the EO, so reducing the amount of signal detected from the IO muscle. It therefore seems likely that the average reflex waveforms observed at this point are predominantly from EO.
Figure 9.5. Ultrasound image showing the different depths of the IO and TrA muscles. The most superficial part of IO is at 0.78cm, the fascia between IO and TrA is at 1.47cm and the deepest part of TrA is measured at 2.04cm. The position of the surface electrodes is indicated by the two red dashes positioned 2cm apart which also highlights how far from the TrA muscle is away from these, as it is short as well as deep. The position of the transducer on the abdomen is shown by the white bars on the schematic of the trunk in the bottom left hand corner of the scan. The illustration below is to aid the identification of the boundaries of the ASIS, IO and TrA.
The IO and underlying TrA muscles recorded from medial to the ASIS are arranged in parallel and therefore the average reflex waveforms detected at this point may indeed consist of some signal from TrA.

Various experiments could be undertaken to investigate the exact nature of the signal detected over EO on the lateral abdominal wall and over IO medial to the ASIS. Reflex activity in a motor unit identified as representing activity in EO from the ongoing EMG less prone to cross talk from the deeper muscle, could be recorded from using post stimulus time histograms. Using fine wire electrodes may also reduce some if not all of the cross talk between EO and IO, and IO and TrA. Finally to distinguish between signals from EO and IO another set of electrodes could be positioned at 90° to those over EO be in line with the underlying IO. The two signals detected simultaneously could then be compared giving some insight into the nature of the signal of each.

**Displacement of the IO and TrA muscles when tapping medial to the ASIS**

Finally it may be that tapping medial to the ASIS stretches the TrA muscle, which underlies both the EO tendon and the IO muscle at this point. If this were the case then the afferent activity evoked would be from TrA and these afferents may contribute to the reflex connection with the opposite IO motoneurone pool. However, as can be seen in figure 9.5 the TrA muscle is over 12mm deep at this point and the force being exerted on the muscle at this depth from the tapper is likely to be much reduced from that on the more superficial EO tendon and IO muscle.
9.2 Analysis of the short latency reflexes in the abdominal and paraspinal muscles.

9.2.1 Confirmation that the short latency responses are spinally mediated.

A comparison of the latency of all five homonymous short latency excitatory reflexes relative to the measured peripheral conduction distances is plotted in figure 9.7. The line of fit passing through these muscles is good ($r=0.96$), indicating that the estimates of conduction distance for the muscles are also good. This line of fit also crosses the x-axis at 3ms, which represents the combined non-conduction delays in these reflex pathways.

Figure 9.6. A plot of estimated conduction distance of each homonymous reflex against the measured latency of each response. The colour code is rectus abdominis (green), internal oblique (red), external oblique (blue), lumbar multifidus (mauve) and iliocostalis lumborum (IC, khaki). With each muscle acting as a reference for the other, the line of fit crosses the x-axis at 3ms, more than the predicted delay for a monosynaptic reflex.

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As already stated the combined central and peripheral non-conduction delays are estimated at approximately 2ms. Therefore, both the good line of fit and the point of intercept at 3ms, close to the estimated 2ms delay, lend some support to the idea of these reflexes being mediated oligosynaptically if not monosynaptically, as would be expected in tendon jerks and H reflexes described in other muscles.

In addition, the range of average latencies for all 32 short latency reflexes observed, is between 11.8ms and 22ms. Bearing in mind the distances from the spinal cord to higher centres and the known conduction velocities of ascending and descending pathways, these latencies are not long enough for the responses to include higher centres. It therefore seems likely that all the short latency reflexes are spinally mediated.

9.2.2 Frequency of occurrence of short latency pathways within and between the abdominal and paraspinal muscles.

The frequency of occurrence of all the short latency reflexes are presented in figure 9.7. As statistical testing cannot be used on the frequency of occurrence data it is worth summarising the pattern of responses between the different muscle groups. Reflexes between the abdominal muscles of both sides occur frequently and are excitatory.
Figure 9.7. Frequency of occurrence of all short latency reflexes between trunk muscles. a) the rectus abdominis (RA), external oblique (EO) and internal oblique (IO) muscles, b) the lumbar multifidus (LM) and iliocostalis lumborum (IC) and c) the IO and LM muscles in response to tapping each muscle.
Those between the paraspinal muscles of the same side occur almost invariably and are excitatory. However, reflexes are less frequently seen between the contralateral paraspinal muscles and when present these are inhibitory in nature. Reflexes between the IO and LM muscles occur infrequently. Taken in isolation this indicates that reflexes between the abdominal muscles and the ipsilateral paraspinal muscles may be more important in the control of trunk muscles than those between contralateral paraspinal muscles and the IO and LM. However, comparisons using measures of potency of each reflex allow more detailed comparisons to be made.

9.3 Amplitude of short latency reflexes within and between the abdominal and paraspinal muscles.

The relative potency of all the reflexes are set out in figure 9.8. The most striking contrast is the different scale needed for each chart. For the short latency reflexes between the abdominal muscles, the iIO reflex is the largest with an amplitude of 985%. In contrast the largest mean response in the paraspinal group is in iLM and this requires a scale of 300%. Finally for the responses between the IO and LM muscles the scale used is 100% (i.e. 1/10\textsuperscript{th} of that between the abdominal muscles). This stark contrast is exemplified by the size of the reflexes in IO and the weakness of the reflexes between IO and LM. It may be related to the effectiveness with which the tap was applied but as the IO is involved in both the most and the least potent reflexes this seems unlikely. Whilst this does highlight the large size of IO related reflexes relative to those in other muscles, this particular issue will be dealt with after those between RA, EO and IO as these comparisons follow on from the initial design of the experiments.
Figure 9.8. Amplitudes (% modulation) of all short latency reflexes between the trunk muscles; a) the rectus abdominis (RA), external oblique (EO) and internal oblique (IO) muscles, b) the lumbar multifidus (LM) and iliocostalis lumborum (IC) and c) the IO and LM muscles in response to tapping each muscle. All data are the arithmetic mean for each response.
9.4 Comparison of the short latency reflexes between the EO and IO muscles.

As stated in the introduction the anatomical arrangement of the EO and IO muscles lead to the proposal that short latency reflex connections exist between these muscles. However, it was predicted that those muscles which are anatomically connected across the midline would be likely to show the greatest degree of muscle afferent connectivity. Correspondingly, those between the i1O and cr1O muscles were expected to show lesser connections than those between i1EO and cr1EO, i1EO and cr1O, and i1O and cr1EO (Askar 1977 & Rizk 1980). What follows is a discussion of these predictions in relation to the reflex connections actually found.

9.4.1 Muscle afferent connections between the EO and IO muscles.

In confirmation of the hypotheses put forward the reflexes between the two EO muscles and the opposite EO and IO muscles of both sides were present in over 75% of the experiments undertaken, and the amplitude of these reflexes was substantial. Thus, in standing at least, the effect of muscle afferent activity from EO and IO on all the oblique muscles is prolific, and suggests a strongly synergistic relationship. This widespread connectivity to muscles on both sides supports the idea of these muscles co-contracting during most movements and loading tasks.

In coming to these conclusions, comment should be made as to the effectiveness of the tap applied medial to the ASIS, which produced reflexes of substantial amplitude. A model was constructed in which the amplitude of the reflexes evoked from EO in isolation were subtracted from the amplitude of reflexes in the same muscle when tapping on both EO and IO medial to the ASIS. This revealed highly skewed reflex
amplitudes in iEO and crEO when tapping medial to the ASIS. In fact the model indicated that there was no effect from iIO to iEO. As IO afferents are widely connected to all five of the other abdominal muscles, this seems unlikely. It does therefore seem likely that tapping medial to the ASIS predominantly activates IO afferents as this produces reflexes of comparable amplitude in all ipsilateral and contralateral muscle pairs.

In contrast to the hypotheses put forward that the reflex connections between iIO and crIO would be less potent than between all other EO and IO muscles, both reflexes (iIO to iIO and iIO to crIO) are at least twice the size of any other reflex evoked in this study. In fact, the amplitudes of the iIO and crIO reflexes are comparable, and can be of remarkably similar character as shown in the results (figure 4.7 and 4.15). In addition, the latency of the crIO reflex is only 1.5 ms longer than that in iIO, a remarkably small difference. It may be that this difference in time is all taken up by the extra distance and therefore extra conduction time between the iIO afferents and the crIO motoneurones relative to the path taken by iIO afferents to the iIO motoneurones. Taken together these observations indicate that the crIO reflex is evoked from iIO afferents and that this connection may be monosynaptic. These ideas are expanded upon and put into context with the relevant literature below. However, before that the experimental evidence from the study utilising vibration requires more detailed discussion.

**Common response to vibration of both iIO and crIO reflexes.**

Vibration of a muscle is known to attenuate the size of a homonymous monosynaptic reflex evoked in the same muscle simultaneously (Barnes & Pompeiano, 1970). One mechanism which may underlie this effect, is that of presynaptic inhibition of Ia afferents acting on other Ia afferents (Desmedt & Godaux, 1978; Stein, 1995). This is
pertinent to this study. The reduction in the size of the homonymous iIO reflex observed during vibration of the iIO muscle is likely to be due to this presynaptic inhibition acting on iO 1a afferents which are evoking the iO reflex at least partly monosynaptically, as might be expected. That the crIO reflex evoked from iIO afferents behaved in the same way, is further support for the notion that this crIO reflex is also evoked by the same reflex connections as the iIO reflex. However this piece of evidence cannot be taken in isolation. Firstly, post activation depression evoked by repetitive activation of the 1a motoneurone synapse via the vibration, is also known to contribute to the reduction in amplitude of reflexes (Katz et al. 1977, Crone & Nielsen 1989 & Hultborn et al. 1996). This effect is probably due to the reduced probability of transmitter release (Lev-Tov & Pinco 1992). Post activation depression could therefore contribute to the reduction in reflex amplitudes seen in this study. However post activation depression can last up to 10-15 seconds, whereas the amplitudes of the reflexes in iIO and crIO were observed to return to at least pre-vibration levels within one or two seconds after the vibration stopped. Secondly, whilst pre-synaptic inhibition is associated with monosynaptic reflex connections it has also been identified as affecting the size of excitatory post synaptic potentials evoked by 1a afferents at the first interneuronal level (Enriquez-Denton et al. 2000). Therefore, this effect of vibration on both ipsilateral and contralateral iO and RA muscles does not in itself support the notion of crossed monosynaptic reflex connections, but does contribute to the overall picture of ipsilateral and contralateral reflexes behaving in a similar manner.

In summary, this similar behaviour of the iIO and crIO reflexes evoked from iIO afferents, the comparable amplitudes of each, the minimal difference in latencies, and the similar reduction in amplitude during vibration, all indicate similar reflex connections to both iIO and crIO muscles. One component of these connections may be
monosynaptic. In addition to this, the reflexes in iEO and crEO, and iRA and crRA from IO afferents are also of comparable amplitude and minimal difference in latency. It does not therefore seem unreasonable to conclude that these reflexes in iEO and crEO and iRA and crRA from IO afferents may also be mediated via similar reflex connections which may also have a monosynaptic component. If these conclusions are correct then it is necessary to compare these findings with previous work on possible pathways across the spinal cord.

**Electrophysiological support for crossed monosynaptic connections.**

Electrophysiological studies in cats suggest the existence of both excitatory and inhibitory short latency crossed reflexes in response to stimulation of low threshold afferents. Various authors have reported crossed inhibitory reflex effects in cats with the majority identifying the pathway as disynaptic (Frank & Sprague, 1959; Curtis *et al.* 1958; Jankowska *et al.* 1978; Jankowska & Odutola, 1980; Wada & Shikaki, 1999). Only Edisen (1967) reports a crossed inhibitory pathway with the attributes of being monosynaptic. In contrast, monosynaptic excitatory crossed reflex effects on contralaterally positioned motoneurones in cats have been reported by Frank & Sprague (1959) Curtis *et al.* (1958) and Wada & Shikaki, (1999). There is therefore evidence in the cat to support a crossed monosynaptic reflex from low threshold afferents to motoneurones positioned in the contralateral ventral horn. The muscles studied by these authors on either side of the cat are synergistic, similar to the abdominal muscles on either side studied in this report. This therefore further supports the idea of crossed monosynaptic connections involving muscle afferents existing between left and right human abdominal muscles.
The morphology of motoneurones and primary afferents.

Evidence from staining techniques suggests three possible arrangements by which a crossed monosynaptic reflex may occur. Firstly, there is the position of the motoneurones supplying the contralateral muscles. So called commissural motoneurones have been identified close to the midline of the spinal cord by Callister et al. (1987) Gordon & Richmond (1991) and Light & Metz (1978). However, only Abrahams & Keane (1984) staining the dorsal ramus of the C2 ramus on one side with horseradish peroxidase (HRP), revealed the presence of motoneurones in lamina VI and VII of the contralateral cervical spinal cord in the cat. Callister et al. (1987) confirmed this finding in cats but could not reproduce it in rats. However, Abrahams & Keane (1984) report the size of these motoneurone cells to be small and suggest they are more consistent with gamma rather than alpha motoneurones, making this finding less relevant as an explanation of the findings in the present study.

Secondly various staining techniques have also revealed the dendritic tree of some groups of motoneurones to be primarily oriented towards and even extending across the midline of the spinal cord. This arrangement in lower vertebrates is well reviewed by Peterson (1989) but has also been demonstrated in both the cervical and lumbosacral spinal cord in kittens (Scheibel & Scheibel, 1973), the sacral spinal cord in cats (Light & Metz, 1978; Jankowska et al. 1978) and the cervical spinal cord in cats (Rose & Richmond, 1981; Ritz et al. 1992; Callister et al. 1987). Medially directed and contralaterally extending dendritic trees would allow synaptic connections from ipsilateral afferents to be formed directly with contralateral motoneurones. This could therefore be the way in which a crossed monosynaptic reflex is formed. However, the majority of the studies referred to show the position of these motoneurones with contralaterally extending dendrites positioned in the dorsomedial aspect of the ventral
horn. The motoneurones pools of the RA, EO and IO muscles are in contrast reported to be situated more laterally in the spinal cord (Miller, 1987; Tani et al. 1994; Holstege et al. 1987). They are mainly situated in the thoracic spinal cord, which has no enlargement so this lateral position is likely to still be close to the midline in this region. Even if these motoneurones were situated more laterally in the ventral horn, motoneurones positioned more laterally in the cat sacrocaudal spinal cord have dendrites which cross the spinal cord (Ritz et al. 1992). Therefore the spread of the dendritic trees of the RA, EO and IO motoneurones allowing the formation of monosynaptic reflex connections remains a possibility. The extent of the dendritic tree of these RA, EO and IO motoneurones has not been reported, but if these dendrites do cross the spinal cord this may contribute to the slightly longer latency of the crossed reflexes relative to the ipsilateral reflex. This is because afferent fibres which synapse on distal parts of motoneurone dendrites are known to produce EPSP’s with a longer latency than those which synapse closer to the motoneurone cell body (Iles, 1977). Therefore, if the Ia afferent fibres from IO synapse on dendrites from the crRA, crEO and crIO motoneurones that cross the spinal cord, the slightly longer latency relative to the ipsilateral reflex would also be compatible with a monosynaptic origin.

Thirdly, there is evidence from staining techniques that primary afferents do cross the spinal cord into both the dorsal horn (as reviewed by Koltzenburg et al. 1999) and the ventral horn (Edisen, 1967; Ritz et al. 1991; Matsushita & Tanami, 1983). These authors report crossed pathways and terminals of primary afferents in the contralateral ventral horn. Whilst the majority of terminal arborisations of these primary afferents from contralateral dorsal roots are situated near the midline, Matsushita & Tanami (1983) illustrate primary afferent fibres extending to the lateral portion of the ventral horn in the sacral and caudal spinal cord of the cat. Should this situation be repeated in
the thoracic and upper lumbar spinal cord where the RA, EO and IO motoneurone pools are situated, this would allow the formation of crossed monosynaptic connections from IO afferents to crRA, crEO and crIO.

If the longer latency of the crossed reflexes relative to the ipsilateral reflexes is taken up entirely by afferent fibres traversing across the spinal cord to directly synapse on the contralateral motoneurones, with only a monosynaptic connection, then the difference in the distances traveled by the ipsilateral and crossed afferents is important. The distance from one ventral horn to the other in the human spinal cord is apparent when using the scale bars accompanying photographic images of the spinal cord reported by Nathan et al. (1990). Between the two ventral horns in the upper lumbar spinal cord where the IO motoneurone pools are cited to be is approximately 2-3mm. In the thoracic region where the RA and EO motoneurones are sited, this distance is approximately 2mm. If the Ia afferents from IO cross the spinal cord within the grey matter, then accepting that the speed of transmission of unmyelinated fibres in this grey matter is 1m/s, the extra distance for the crossed afferent to travel would account for 2-3ms extra conduction time. Of course, the extent of the extra distance for the primary afferent to synapse on the contralateral motoneurone pool compared to the ipsilateral motoneurone pool, would depend upon the course taken by both sets of Ia afferents once in the spinal cord. However, it does not seem unreasonable to suggest that the longer latency of the crossed reflexes is consistent with the extra distance the afferent fibres must traverse across the spinal cord. If so, then both ipsilateral and contralateral reflexes could well be monosynaptic.

This discussion has focused on the monosynaptic component of the homonymous and heteronymous reflexes, in particular the responses in the contralateral muscles. This
emphasis needs to be put into context of the known effects of tapping a muscle/tendon. Reflex effects produced by Ia muscle afferents are mediated monosynaptically, but these connections are unique only to the first 0.6ms of such responses (Hultborn et al. 1987, Katz et al. 1988, Meunier & Pierrot-Deseilligny, 1998). Magladery et al. (1951) demonstrated that the first motoneurones discharging in the H reflex do so at a monosynaptic latency and complementing this the early part of the response evoked by a tendon tap is known to represent purely monosynaptic connections as it occurs at the same latency as the H reflex in the motoneurones recruited first (Ashby & Labelle, 1977, Ashby & Zilm, 1982, Mao et al. 1984). As there is ample time for the motoneurones recruited later to be influenced by non-monosynaptic connections (Burke et al 1984, Marchand-Pauvert & Nielsen, 2002), it seems likely that at least some of the response beyond the first 0.6ms is non-monosynaptic, being interneuronally mediated. In contrast some of the later responses are likely to be produced by slower conducting Ia muscle afferents still making monosynaptic connections. However, it is unclear exactly which pathways do contribute to the later part of the responses seen. If more than one pathway is involved, then the relative contributions of each are also unknown.

9.4.2 Functional implications of oblique muscle co-activation.

Co-activation of all four oblique muscles is commonly reported in EMG studies of trunk movement and loading (Beith et al. 2001; Huang et al. 2001; McGill, 1991; Peach et al. 1998; Pope et al. 1986; Thelen et al. 1995; Zedka et al. 1999; Zetterberg et al. 1987). That all four abdominal oblique muscles are coupled via Ia muscle afferent connectivity compliments these studies. However, the reflexes between the left and right IO muscles form the most potent of the reflex connections, even though they are not connected anatomically across the anterior abdomen as all the other oblique muscles are. So why are the IO muscles so strongly connected?
9.4.3 Anatomical connections between the IO and TrA muscles

One explanation for the strength of the crossed reflexes between the IO muscles may relate to the attachments of the abdominal oblique muscles. The bony attachment of the IO muscles lateral to the point at which the EMG data was recorded from is to the inner rim of the pelvis anteriorly (figure 9.9). From this attachment it connects contralaterally with both deep (TrA) and superficial (EO) abdominal muscles of the other side. It may be that these crossed muscle afferent connections from IO to the crIO muscle, relates to a stabilising role for both the left and right IO muscles in unison, via attachments between the IO and TrA on opposite sides. These muscles on opposite sides exert a pull on the left and right iliac bones. Pulling these bones together anteriorly contributes to what has been termed force closure of the sacroiliac joints in the posterior part of the pelvic ring (Pool-Goudzwaard et al. 1998; Richardson et al. 2002). Force closure is thought to be important in contributing to the stability of the sacroiliac joint. The mechanical advantage of the IO muscles relative to the sacroiliac joint is considerable and therefore may contribute to the stability of the joint. This may be a further reason for both the strength and symmetry of the reflexes associated with the IO muscles.

In addition, the strength of the IO reflexes may help to create a stable platform for co-activation of the iIO and the crEO, as these two muscles are attached (figures 9.9 & 9.10). The IO may be an intermediary muscle linking both deep (TrA) and superficial (EO) muscle groups of the contralateral side so anchoring them to the pelvis. If the three muscles are viewed anteriorly they form a connection not unlike a car seat belt (figure 9.10). The extensive reflex connections observed in this study may compliment these anatomical connections, and help to produce stability of both the pelvis and the trunk. Whether the reflex connectivity also exists between IO and TrA remains to be investigated.
Figure 9.9. The anatomical connections between the muscles of the anterolateral abdominal wall on either side. Cross sectional view below the umbilicus showing the connections between the IO on one side and the EO and TrA of the opposite side (taken from the work of (Askar 1977; Rizk 1980). The blue muscle is the external oblique, the red muscle is the internal oblique, the black muscle is the transversus abdominis and the green muscle is the rectus abdominis.

Figure 9.10. Anatomical connections between the external oblique (blue) and part of the transversus abdominis muscles (black) on one side, to the internal oblique (red) on the opposite side, (rectus abdominis is in green). This creates a type of seat belt arrangement. For clarity the homologous EO, IO and TrA muscles are not shown but would when in situ, form a similar arrangement in the opposite direction.
9.5 Short latency reflexes involving the RA muscles.

As for EO and IO the anatomical arrangement of the left and right RA muscles lead to the proposal that there may be short latency reflex connections between them. Being situated immediately either side of midline, oriented almost in parallel and connecting the thorax and pelvis suggests a common function in producing flexion of the trunk. EMG studies confirm that the muscles usually work in unison (DeSousa & Furlani, 1974; Pope et al. 1986). The high frequency of occurrence of a reflex in crRA when tapping iRA, the non significant difference in amplitude of these reflexes in iRA and crRA, and the slightly longer latency of the crRA reflex relative to that of iRA indicates that the muscles have very closely linked reflex connections. In addition, as found in the iO and crO muscles, the effect of vibration on the iRA reduces the amplitude of both iRA and crRA short latency reflexes. Once again it seems likely that this is due to presynaptic inhibition of the RA Ia afferents acting on other RA Ia afferents which produce monosynaptic reflexes. This indicates that both ipsilateral and contralateral RA reflexes may be monosynaptic. The arguments put forward for such a crossed connection between the IO muscles are therefore also pertinent for those between the left and right RA muscles.

The RA and EO muscles are positioned on either side of the trunk with the EO being further from the midline. In addition, the RA and EO muscles on the same side may act together to produce or control side bending. However, there is also enough difference in the position and fibre direction of the muscles, with the EO being more obliquely orientated, for each muscle to work independently of one another. In fact, the amplitudes of the four reflexes between RA and EO muscles on both sides when tapping either RA or EO, were small compared to those between EO and IO. For each reflex the amplitude was on average less than 100% (when including the experiments in
which no response was observed). In addition, the reflex from iEO to crRA was the least prevalent of all abdominal muscle reflexes occurring only twice (2/11), and was significantly smaller in amplitude than the iEO to iRA response. It seems therefore that the distribution of the EO afferents is biased towards the iRA rather than the crRA, but this is not the case from the RA afferents to the EO muscles. The overall strength of these reflexes relative to all the others may indicate their relative contribution to the reflex control of trunk muscles.

As the RA and IO muscles are almost at right angles to one another, this pair of muscles seems the least likely to exhibit synergistic connections. However, co-activation of these muscles has been observed (Pope et al. 1986) and the results of the present study show that short latency reflexes do exist between them. In contrast to those between RA and EO, there is no difference between the size of the reflexes in the iRA and crRA when tapping IO or in iIO and crIO when tapping RA. However, the reflexes in the RA muscles from the IO afferents occur more frequently, and are more potent than from RA to either IO muscle. Therefore, compared to the reflexes between EO and RA, these responses are prolific and potent especially from the IO to RA. Once again this highlights the considerable contribution of the IO afferents to the reflex control of trunk muscles.

9.5.1 Comparison of the effectiveness of RA, EO and IO muscle afferents, and the receptiveness of the RA, EO and IO muscles

Comparison of the relative amplitude of all the abdominal muscle reflexes indicates that those reflexes involving the IO muscle are more potent than those involving EO, which are in turn more potent than those involving the RA muscle. To allow a more direct
comparison, the relative amplitudes of all six reflexes that each group of afferents and each group of muscles are involved in were pooled and an average value for each obtained. Whether this is calculated by ranking them one to eighteen and then comparing the sum of the ranks, or using the mean of the six average responses each is involved in, the relative strength of each remains the same (figure 9.11).

![Figure 9.11](image.png)

Figure 9.11. The relative effectiveness of and receptiveness to reflex activation of rectus abdominis (RA), external oblique (EO) and internal oblique (IO) afferents and muscles. The mean of the six responses evoked by or in each muscle or afferent, are presented in rank order.

The most obvious aspect of this analysis is that the IO muscle is indeed more effective and affected than the EO, and this muscle in turn in shows greater effects than the RA. This marked difference is unexpected. The question is therefore raised as to why muscle afferent activity should be so dominant to and from the IO muscle and so much weaker to and from RA.
One possible explanation for these differences may relate to higher levels of background EMG within the IO muscle compared to EO and RA as has been identified in this study, and in standing subjects by Floyd & Silver (1950). However, this factor alone should not affect the size of the reflexes relative to the levels of EMG. This is due to automatic gain control, whereby a reflex response remains an approximately constant proportion of the ongoing EMG levels in the same muscle (Harrison & Taylor, 1981; Matthews, 1986; Prochazka, 1989). Also the smaller size of reflexes in the RA muscle may have been due to these reflexes not always being apparent when elicited in standing as these amplitudes were calculated when including those experiments in which no reflex was observed, as nought. However, leaning back did reveal the RA reflexes in all subjects, but this made little difference to the amplitude of these reflexes. One further alternative may be that the arrangement of the muscle, tendons and tapper makes the tap applied to IO more effective than when applied to EO, and likewise to EO when compared to RA. Whilst this may account for some of the difference in the size of reflexes evoked from the different afferents, it cannot explain the greater receptivity in IO over EO and in EO over RA. It also seems unlikely that the magnitude of the differences in reflex amplitudes evoked is due entirely to differences in the application of the tap on RA, EO and IO.

Therefore, there does seem to be a bias in the size of the reflexes within the abdominal muscles towards those situated more deeply and arranged to provide stability. In standing the main role of these muscles is likely to be maintenance of posture. As the IO muscles are ideally situated to aid the maintenance of posture this may be the reason why the gain of the reflexes to and from this muscle are so much higher. Intriguingly, the IO afferents produce more potent effects than the IO muscle receives, whereas the EO and RA muscles are more receptive than their afferents are effective. This leads to
the conclusion that the effect of muscle afferents from within the IO muscle are, at least in standing, the most potent factor in the short latency muscle afferent evoked control of the human trunk muscles (excluding TrA which was not been studied). This is further supported by the symmetrical distribution of the effects to the IO muscle and from the IO afferents. When IO afferents and/or the IO muscles are involved in these reflexes there is never a significant difference in the size of the ipsilateral and contralateral effects between homologous pairs. The even distribution of the reflexes in the IO muscles on both sides may be indicative of a need for co-activation of comparable magnitude in the IO muscles on each side, irrespective of which muscle afferents evoke the activity. As shown in figures 9.9 and 9.10, the IO could be described as forming an anchor point on the iliac bones of either side for both the opposite TrA and the opposite EO. If this is an important part of its role then symmetry of the EMG activity and forces induced in the left and right homologous muscle pairs, would be important. The fact that IO afferents are also evenly distributed to EO and RA muscles on both sides indicates a similar role for RA, EO and IO muscles on both sides in the maintenance of posture. That the size of the reflexes in IO are greater than those in EO and these in turn are larger than in RA, may indicate the contribution made by each of these muscles in maintaining posture and stability.

An alternative reason for the different potency of the reflexes involving different afferents and muscles, may be the ease with which the stretch can be applied to each muscle in everyday tasks. The IO muscle afferents stimulated in this study are situated between the two pelvic bones, and these are probably less affected by movement of the vertebral column. Trunk rotation may produce the greatest stretch in IO via the attachment to the crEO, but even then this stretch in IO seems likely to be less than that in EO. The functional manoeuvre in which the IO muscle is stretched most is
inspiration involving the diaphragm, but even these changes in length are likely to be less during quiet respiration. Therefore, the slope of the gain in the reflexes evoked from IO afferents may be steep to facilitate activation of IO, especially in standing. In support of this argument the reflex responses in IO were difficult to evoke with subjects in supine. In contrast, for both RA and EO muscles, movement within the trunk (i.e. flexion, extension, rotation and side bending) will change the length of these muscles more. However strong reflexes evoked from either EO or RA in response to changes in length would prevent easy free flowing movement of the trunk. It may be that stretch reflexes within the abdominal muscles are predominantly set to those muscles which aid stability and posture rather than controlling movement.

In summary, the ease with which the reflexes involving the IO muscles are evoked relative to those involving EO and RA, is probably necessary for different reasons, each of which is related to the production of stability of the trunk, pelvis and vertebral column. Aiding stability in such a way will in turn contribute to the maintenance and control of posture.

9.6 Short latency reflexes between the ipsilateral and contralateral LM and IC muscles.

The experiments involving the paraspinal muscles were designed to investigate any differences in the control of the LM and IC muscles, both ipsilaterally and contralaterally. Whilst some aspects of the positions of these two muscles are similar, differences in the reflex control between these muscles may be expected because of their different anatomical arrangements. In particular the LM attaches to the vertebral column and the sacrum, whilst the IC attaches to the thorax and the pelvis.
9.6.1 Short latency excitatory reflexes between the ipsilateral LM and IC muscles.

The muscle fibres of IC and LM muscles on the same side of the lumbar spine are both directed downwards but also converge slightly. This may affect some aspects of their function but they are still ideally positioned to work synergistically to produce extension and side bending of the lumbar spine, with the IC predominating in the latter due a greater mechanical advantage. Therefore the heteronymous excitatory reflexes seen between these two muscles on the same side are perhaps unsurprising.

The only difference between these reflexes is that the homonymous reflex in LM is on average larger than the homonymous response in IC and the heteronymous response evoked from IC afferents to the LM muscle. This suggests that the LM afferents may produce more potent effects than those from IC afferents. The only caveat to this conclusion is that overlying the LM muscle is the extended tendon of the thoracic erector spinae (ES) muscle, which is in parallel to the IC muscle. The erector spinae tendon may therefore be stretched when tapping on LM and this may produce some activation of muscle spindles in the erector spinae muscle positioned higher up. If these afferents in the thoracic spine do make reflex connections with the muscles lower down in the lumbar spine, this may account for some or all of the difference in larger amplitude of the responses in LM compared to IC. Not withstanding these points, the main conclusion that the ipsilaterally positioned LM and IC muscles exhibit synergistic reflex connectivity is indeed unsurprising.
9.6.2 Short latency reflexes in the contralateral LM and IC muscles.

The earliest response seen in the contralateral paraspinal muscles was an occasional short latency excitatory response observed in the crLM when tapping iLM. However this response was not always seen, and when present was weak. It is difficult to interpret these as being evoked via reflex pathways across the spinal cord in the light of experiments undertaken by Tani *et al.* (1997). These authors tapped on the interspinous ligament, which evoked short latency reflexes in ES on both sides. They interpreted the responses observed in the ES muscles distant from the tap as being evoked by the mechanical effects of the tap spreading to the ES muscles, and thereby evoking a homonymous response. As the difference in latency was minimal for reflexes at different levels, and probably too short for transmission via pathways up or down the spinal cord, this conclusion is reasonable. Experiments undertaken in this study tapping on the spinous processes of L2 in the midline produced similar short latency responses in both LM muscles. In the light of these findings it is not possible to definitively confirm whether the excitatory responses in crLM are evoked by spread of the mechanical wave of vibration. However, even if they are heteronymous reflexes their infrequent occurrence and small amplitude is in stark contrast with the more frequently occurring and larger amplitude short latency excitatory responses between iLM and iIC muscles, and between the abdominal muscles.

Whilst the existence of excitatory crossed reflexes between the paraspinal muscles may be in doubt, the short latency crossed inhibitory reflexes are obvious. Indeed Zedka *et al.* (1999) report a similar crossed inhibition in the more laterally positioned ES muscles in response to a similar tap in all subjects tested (n=5). This contrasts with the excitatory reflexes between contralaterally positioned abdominal muscles. One might expect such short latency inhibition in muscles positioned either side of a joint with a
more obvious antagonistic function. That this inhibition occurs more frequently in the crLM than the crIC is intriguing. Whilst this does reveal differences in the control of IC and LM it was not expected. Overall the left and right LM muscles which attach either side of the vertebral column exhibit more reflex connections than the left and right IC muscles, which being more laterally positioned are more obvious antagonists. In fact, the function of this short latency inhibition is unclear. Even the long latency between the ipsilateral homonymous response and the inhibition (over 8ms) suggests it is not the disynaptic pathway which is so often associated with antagonistic muscles.

One further useful comparison of the reflex control of the left and right LM muscles can be made with the reflex control of trapezius (Alexander & Harrison, 2002). This comparison is interesting as the attachments of the trapezius and LM muscles are similar, with both left and right muscles attaching to either side of the same vertebrae across multiple segments. However, in contrast to the crossed inhibition seen between the LM muscles on either side, the reflex connections between trapezius are excitatory. Why should this be? Firstly, the girdle bone to which each attaches have different functions. The scapula to which the trapezius attaches at the base of the upper limb is mobile with the function of positioning the gleno-humeral joint for upper limb tasks. The trapezius is thought to provide stability for the scapula. The bilateral control of these muscles may aid the contralateral trapezius muscle in stabilising the proximal attachment of the contracting ipsilateral trapezius. The iliac bone to which the LM attaches at the base of the lower limb forms part of the more rigid pelvis. The crossed inhibition may aid movements in the frontal plane, as in this plane the left and right muscles act antagonistically. The second factor relates to the multisegmented arrangement of the LM. At its most superficial, nearest to the recording surface electrodes it can span five segments (i.e. L1- ilium). In its deepest portions it is
unisegmental and adjacent to the underlying bone and facet joints. Recent evidence suggests that the superficial portion of LM being recorded from is controlled differently from the deeper less accessible muscle fibres on the same side (Moseley et al. 2002). It may be that the deeper unisegmental LM muscles exhibit the short latency crossed excitatory pathways exhibited between the abdominal muscle and the trapezius. In support of the idea of a different control of deep and superficial muscle fibres Trontelj et al. (1979) report differential activity in the deep and superficial ES muscle at the L4 level in response to tapping the vertebral column, in standing and side bending. When the deep fibres demonstrated a reflex the superficial fibres did not and vice versa.

In summary, the crossed reflexes between the paraspinal muscles are when present inhibitory, which is in contrast to the excitation seen between the abdominal muscles on opposite sides. The most potent reflexes within the paraspinal group are those involving the LM muscles, a pattern similar to those seen in the IO muscles compared to the EO and RA in the abdomen. This may indicate a preferential control of the LM muscle by reflex pathways compared to that in IC based on the definition of being local, although the contrast is nowhere near as obvious as between IO and both EO and RA. Whereas this more potent reflex control of IO may aid stability of the trunk, the same argument is not so clear cut for the LM muscles.

9.7 Short latency reflexes between the IO and LM muscles.

The experiments investigating possible short latency reflexes between the IO and LM were undertaken because both muscles are thought to contribute to the stability of the lumbar spine by virtue of their attachments to the lumbar spine. To this end, these experiments investigated whether short latency heteronymous reflex connections exist between two muscles on opposite aspects of the trunk. Both the frequency of
occurrence and amplitude of these reflexes suggest that even when the reflexes are
evident, they are not strong. None of the reflexes identified are apparent in more than
40% of experiments undertaken. Those from IO to LM are the least prevalent and are
never of substantial amplitude. The responses in IO resulting from tapping the LM
muscle are slightly more prevalent and are always excitatory. In some instances,
however they may be produced homonymously, as the tap applied on the LM muscle
may also stretch the proximal attachment of IO, the thoraco-lumbar fascia (Bogduk &
Macintosh, 1984). However, in five experiments reflexes were observed in the crIO
muscles in isolation from any reflex in iIO, a reflex that cannot be homonymous. It
may be therefore that these reflexes from LM to iIO and crIO do exist. However,
relative to the reflexes seen elsewhere between the abdominal and paraspinal muscles,
they are not potent. That LM to IO reflexes occur more frequently than from IO to LM
indicates these reflexes may be unidirectional. The anatomical arrangement of both
muscles means that the LM is more likely to be stretched during trunk movements than
the IO. Therefore any short latency reflexes from LM to IO, may be responsible for
aiding stability during movement, rather than in response to the smaller perturbations
which may be associated with the IO afferents to the abdominal muscles.
9.8 Summary of all reflexes within and between the abdominal, and paraspinal muscles.

When comparing all 32 short latency reflexes observed within and between the abdominal and paraspinal muscles, some stark contrasts are apparent. The most obvious differences are:

- the reflexes between the abdominal muscles on both sides are excitatory, whereas those between the left and right paraspinal muscles are when present inhibitory.
- the amplitudes of the abdominal muscle reflexes evoked in IO are greater than EO, which are in turn greater than those in the RA muscle.
- the reflexes between the IO and LM muscles occur infrequently and when apparent are weak.

The contrast in the amplitudes of the reflexes evoked in IO and to a lesser extent EO compared to the RA, suggests a stabilising role for IO. This compliments the existing evidence from both EMG and biomechanical studies. There is a contrast between the contralateral excitation seen between the abdominals, and the contralateral inhibition or no response between the left and right paraspinal muscles. This is mirrored in various studies of the activation patterns of these muscles in which co-activation throughout almost all tasks is seen between abdominal muscles, but not between the contralateral paraspinals. Finally some authors have described co-activation of the abdominal muscles during activity of the paraspinal muscles, but not vice versa. Therefore, the infrequent occurrence and small amplitudes of pathways between the IO and LM may or may not have been expected.
10 INVESTIGATING POSSIBLE ASYMMETRY IN THE SHORT LATENCY REFLEXES BETWEEN THE LEFT AND RIGHT IO MUSCLES.

10.1 Introduction.

Preliminary analysis of the short latency reflexes in the iIO and crIO to tapping on the iIO muscle revealed an asymmetry in the amplitudes of the reflexes. In a small number of subjects the reflex in one or other of the IO muscles, was consistently larger than the other irrespective of whether the tap was applied ipsilaterally, or contralaterally. This effect was therefore investigated further.

10.2 Method.

As illustrated in figure 10.1 taps were applied in the midline to produce an equal stretch in both IO muscles, and to both IO muscles medial to each ASIS to evoke afferent activity from each IO muscle in isolation. The data is mostly that which is reported in chapters 4 and 8. In all, 18 subjects were tested including two subjects in whom the experiments were repeated three months apart. As for the experiments already described 30 taps were applied at each point. The number of experiments undertaken for each subject varied as the data was also being used for the previous study, which included the investigation of the effect of interstimulus interval on the reflexes evoked. The data was then rectified and averaged and the maximum amplitude measured and expressed as a percentage of background mean EMG activity.
10.3 Results.

As shown in chapters 4 & 8 reflexes were evoked in all subjects when tapping at all three points. In 10 of the 18 subjects the amplitude of the reflexes in the left and right IO muscles varied relative to one another when tapping at the three different positions. In two of the 18 subjects, pooled data from at least three experiments showed an asymmetry in that the response in either left or right IO was always larger. However, this was not always the case for each of the experiments undertaken. In a further four subjects the reflex evoked in one of the IO muscles was always the largest irrespective of where the tap was applied. However for these four subjects the experiment was only undertaken once. Bearing in mind the variability of the results in the first 10 subjects and the two subjects who only showed asymmetry when the data was pooled, this may not necessarily reflect a true bias towards one IO muscle. In two subjects the full experimental protocol was undertaken on two occasions three months apart. In both instances the reflex was always largest in the same muscle (in both cases the right IO, see figure 10.1). One of these subjects has a known scoliosis, although in this subject the condition is not disabling.

10.4 Discussion.

These findings, although incomplete, indicate that asymmetry of the reflex control of the left and right IO muscles may exist in some asymptomatic subjects. That such asymmetry was also found in the one scoliotic subject tested may indicate this finding is more common in this condition. Possible asymmetry of reflex activity between the left and right sides of the body has been investigated in different reflexes in different situations.
Figure 10.1. Asymmetry in the amplitude of the reflexes in left and right internal oblique muscles. The upper illustration shows the experimental arrangement to investigate the relative amplitude of short latency reflexes in the left and right internal oblique muscles when tapping ipsilateral, contralateral and in the midline relative to each muscle. The point at which the tap is applied is shown by the X's, and the electrode placements as the pairs of black dots. The data below shows short latency reflexes in the left and right IO muscles (left-blue, right-red) to tapping the left IO (LIO), right IO (RIO) and in the midline. The right IO reflex is larger irrespective of which muscle is tapped. This subject has a known scoliosis of the spine. The data has been rectified, then averaged and the right IO data has been normalised to that of the left IO.
Zabelis et al. (1998) showed no difference between left and right knee and ankle jerks, during and without the jendrassik manoeuvre being performed. In contrast, Kassem & Evinger (2001) report the size of the blink reflex in one eye to be consistently of shorter latency and larger amplitude, irrespective of whether the left or right supraorbital branch of the trigeminal nerve was electrically stimulated. However, the reflex amplitudes reported in this study were not normalised to background EMG activity. Because of automatic gain compensation, (Harrison, 1987; Matthews, 1986; Prochazka, 1989) comparing measures of absolute amplitude between different reflexes cannot definitively reveal differences in motoneurone excitability. This leaves a question mark as to whether real differences in the amplitudes of the blink reflex between sides reported by Kassem & Evinger (2001) exists. However, Goode et al. (1980) studying the recovery curve of the soleus H reflex between left and right sides, do report differences in the recovery curve on either side. (As this technique compares differences between reflexes in the same muscle and not absolute amplitudes the data does not need to be normalised). They suggest the most likely explanation is related to cortical laterality, as the H reflex recovery curve has been shown to be affected after lesions of the descending corticospinal tract. In addition, the superficial abdominal skin reflex of the abdominal muscles as evoked by a scratch, has been shown to be asymmetrical in normal subjects (Teasdall, 1970). Therefore, asymmetry of reflexes in left and right homologous muscle may in some instances be a finding in normal subjects.

In relation to scoliosis, Riddle & Roaf (1955) Zuk (1962) Zuk (1968) and Redford et al. (1969) have reported greater EMG activity in the muscles at the apex of the convexity of the scoliotic curve in humans. Trontelj et al. (1979) tapped on the vertebral column in the midline, and recorded from the paraspinal muscles on either side. They
highlighted a greater absolute amplitude of the reflex activity in muscles on the convex side of scoliotic subjects. Whilst this analysis of non-normalised data does not allow for a definitive comparison, as highlighted above, it seems unlikely that the reflex on the convex side would be of greater amplitude in all subjects by chance. These studies therefore suggest that the muscles on the convex side of a scoliosis may exhibit an increase in EMG activity and receptiveness to afferent input. However, Hoogmartens & Basmajian (1976) studied scoliotic subjects using the tonic vibration reflex. They revealed hypersensitivity of the muscle spindle system in the paraspinal muscles on the concave side in 15 of 23 subjects, but in only 5 of the 23 subjects on the convex side. So whilst there is some evidence to suggest alterations in the control of the paraspinal muscles in scoliotic subjects, the results do not equivocally implicate either the concave or convex side.

Prior to the results reported in this study, no data has been available of any asymmetry in the control of the abdominal muscles, in subjects with an underlying scoliosis. The preliminary findings reported here therefore now need to be extended, to clarify if a) asymmetry of reflex activity between the IO muscles is common in asymptomatic subjects and b) whether it is always the case in subjects with scoliosis. It is also worth noting that Cruccu et al. (1992) identified a delay in the latency and a reduction in amplitude of jaw muscle reflexes in those muscles overlying a painful temperomandibular joint compared to the same joint on the opposite side in the same subjects. It also remains to be seen if the reflexes to the left and right IO muscles are similarly affected in back pain, particularly pain which is perceived predominantly on one side.
11 RESULTS 6 -
LONG LATENCY REFLEXES IN THE ABDOMINAL AND PARASPINAL MUSCLES.

11.1 Long latency reflexes in the abdominal muscles in response to tapping the abdominal muscles.

All the reflexes seen in both ipsilateral and contralateral RA, EO and IO muscles in response to tapping RA, EO and IO respectively were excitatory. The predominant effects were observed when tapping the RA muscle in standing (figure 11.1). The responses seen in both the iliO and crIIO muscles when tapping the RA occurred in all experiments (figure 11.2). Reflexes were also seen in both EO muscles 83% of the time (10/12), in the iRA 52% of the time (11/21) and in crRA 62% of the time (13/21). The amplitude of these reflexes evoked when tapping on RA range from 116±21% (mean±SEM) in crRA to 193±27% in iliO (figure 11.3).

In contrast, the long latency reflexes evoked in the RA, EO and IO muscles when tapping the EO muscle belly and IO muscle/tendon were less frequently seen, never being apparent more than 50% of the time (figure 11.2). The mean amplitudes of these responses are also on average lower than from tapping RA (figure 11.3).
Figure 11.1. Wide ranging long latency reflexes in rectus abdominis (RA), external oblique (EO), and internal oblique (IO) muscles in response to tapping the RA muscle. (The point tapped is indicated by an X, and the position of recording electrodes by pairs of black dots. (i – ipsilateral, cr – contralateral)
Figure 11.2. Frequency of occurrence of long latency reflexes in rectus abdominis (RA), external oblique (EO) and internal oblique (IO) muscles when tapping the same muscles in standing. (i - ipsilateral, cr - contralateral).

Figure 11.3. Mean amplitudes of long latency reflexes between rectus abdominis (RA), external oblique (EO), internal oblique (IO), excluding experiments showing no responses. (i - ipsilateral, cr - contralateral).
11.2 Long latency reflexes in the IC and LM muscles when tapping the IC and LM muscles.

When tapping the IC and LM muscles respectively long latency excitatory reflexes were observed in the IC and LM muscles on both sides (figure 11.4). These reflexes occurred between 50% (IC to iIC) and 25% of occasions (IC to both iLM and crLM, figure 11.5). The amplitude of these reflexes are illustrated and arranged for comparison in figure 11.6. This pattern of longer latency excitation for all extensor muscles when tapping on one extensor muscle is in contrast to the inhibition seen contralaterally at short latency in response to the same tap.

Figure 11.4. Long latency excitatory reflexes in the lumbar multifidus (LM) and iliocostalis lumborum (IC) muscles. The records in a) illustrate the effect when tapping the LM muscle and in b) when tapping IC as indicated by the illustration on the left. (i – ipsilateral, cr – contralateral)
Figure 11.5. Frequency of occurrence of long latency reflexes in the iliocostalis lumborum (IC), and lumbar multifidus (LM) muscles when tapping the same muscles. (i – ipsilateral, cr – contralateral).

Figure 11.6. Mean amplitudes of the longer latency excitatory reflexes in the iliocostalis lumborum (IC) and lumbar multifidus (LM) muscles in response to tapping IC and LM respectively. (i – ipsilateral, cr – contralateral).
11.3 Long latency reflexes between the abdominal and paraspinal muscles.

Long latency reflexes were also seen in the IO muscles when tapping the LM, and in LM when tapping IO. These effects were predominantly inhibitory. This was most obvious in the IO muscle when tapping LM (figure 11.7). The inhibition occurred 50% of the time in the iIO (18/36) and 39% of the time in the crIO (14/36, figure 11.9). This inhibition was immediately followed by an excitation in the majority of experiments but the excitation was never seen in isolation, or prior to the inhibition, (but see IO to LM below). The amplitudes of the long latency reflexes in the IO muscles are illustrated and arranged for comparison in figure 11.10.

![Diagram of muscles with reflexes](image)

Figure 11.7. Long latency excitatory reflexes in the lumbar multifidus (LM) muscles and long latency inhibitory reflexes in the internal oblique (IO) muscles in response to tapping the LM muscle. The point tapped on the LM is illustrated with the X, and the position of the surface electrodes over each muscle group by pairs of back dots opposite the relevant data. (i – ipsilateral, cr – contralateral). All traces are the average of 30 sweeps of rectified data.
The long latency reflexes in both left and right LM muscles to tapping the IO muscle on the anterior abdomen when present usually consisted of a reduction in background EMG followed by an increase in EMG levels (figure 11.6). The inhibitory responses were present 29% of the time (10/34) and the excitatory responses were present 35% of the time (12/34, figure 11.9). Whenever an inhibition was present this always preceded the excitation. However, in two experiments the inhibition could not be confirmed as being present as any change in EMG level did not exceed 2SD, whereas the excitation was obvious (figure 11.8 subject 3). The amplitudes of the long latency reflexes in the LM muscles when tapping the IO are illustrated and arranged for comparison in figure 11.10.

Figure 11.8. Long latency inhibitory reflexes in the lumbar multifidus muscle (LM) in response to tapping the IO muscle in the midline. The point tapped on the anterior abdomen is illustrated with an X, and the position of the surface electrodes are indicated by the pairs of black dots on the upper diagram over IO, and on the lower diagram over LM.
Figure 11.9. Frequency of occurrence of long latency reflexes in internal oblique (IO) and lumbar multifidus (LM) muscles to tapping the same muscles. (i – ipsilateral, cr – contralateral).

Figure 11.10. Mean amplitudes of the longer latency excitatory reflexes between internal oblique (IO) and lumbar multifidus (LM) muscles in response to tapping IO and LM respectively, including only observed responses. (i – ipsilateral, cr – contralateral).
11.4 Analysis of the amplitudes of the long latency reflexes in the abdominal and paraspinal muscles.

Comparison of the long latency reflexes identified in the abdominal and paraspinal muscles was carried out in a manner similar to that for the short latency reflexes (figure 11.11). Thus, the different reflexes were compared using the mean amplitude calculated when including those occasions where no effect was observed (these were given the value zero). Where appropriate, parametric statistical analysis in the form of a one way ANOVA or paired t-tests were used with either logarithmically transformed data to achieve homogeneity of variance, or non-transformed data. For some tests however, homogeneity of variance could not be achieved with or without transformed data and therefore non-parametric tests in the form of the Kruskal-Wallis test and the Mann Whitney U test as the non-parametric post hoc equivalent were performed.

11.4.1 Comparison of the amplitudes of long latency reflexes in the trunk muscles.

Tapping on the RA muscle produces larger amplitude reflexes in all abdominal muscles than tapping on EO and IO, except in the iRA (see figure 11.11). Tapping on the EO and IO muscles produced long latency reflexes in all muscles, which are not significantly different in amplitude from each other except the iIO muscle. In this muscle tapping on EO produced a larger reflex than tapping on IO (figure 11.11). The amplitude of the long latency reflexes between the homologous RA, EO and IO muscle pairs when tapping on the RA, EO and IO muscles were never significantly different. Therefore, to simplify the analysis the data from these homologous pairs was combined to allow comparison of the reflexes in each type of muscle when tapping on RA, EO and IO. This revealed significantly greater amplitude responses in IO than either RA or
EO when tapping on the RA muscle. The size of the long latency reflexes in RA, EO and IO when tapping on EO and IO were never significantly different from each other. Therefore, the largest amplitude excitatory long latency reflexes were evoked by tapping on the RA muscle. Of these the heteronymous reflexes to both IO muscles was the most potent and these were the only long latency reflexes to occur in all subjects tested.

The amplitudes of the long latency reflexes between IC and LM of both sides (figure 11.11) were not significantly different (p=0.262, Kruskal-Wallis test), neither were those between IO and LM (p=0.58, Kruskal-Wallis test).
Figure 11.11. Mean amplitudes of all long latency reflexes between rectus abdominis (RA), external oblique (EO), internal oblique (IO), iliocostalis lumborum (IC) and lumbar multifidus (LM) muscles. The data includes those experiments where no response was observed. Such data points were given the values of zero. (i – ipsilateral, cr – contralateral).
11.5 Latencies of the long latency reflexes in the abdominal and paraspinal muscles.

The latencies of the 29 long latency responses observed in the abdominal and paraspinal muscles occurred within a window of 10.2ms, which ranged from 45.3ms to 55.5ms and these are all shown in figure 11.12. Whichever afferents are responsible for evoking these responses, the relatively narrow range of latencies of 10.2ms may indicate that all the reflexes have a common pathway within the central nervous system.

![Diagram of reflexes between various muscle groups](image)

Figure 11.12. Mean latency of long latency reflexes between rectus abdominis (RA), external oblique (EO), internal oblique (IO), iliocostalis lumborum (IC) and lumbar multifidus (LM) muscles. (i – ipsilateral, cr – contralateral). Horizontal lines separate the reflexes between the abdominal muscles, the paraspinals muscles and those between IO and LM.
11.6 Long latency reflexes in the abdominal muscles when leaning back.

The reflexes evoked from tapping on the RA muscle were evoked in both standing and leaning back. Therefore, in a small number of subjects (n=5) the same two positions were also used to evoke reflexes from tapping on EO and IO, to compare the effectiveness of the different afferents in both standing and leaning back. The effect of leaning back on the long latency excitatory reflexes in the abdominal muscles produces contrasting results for the 18 reflex responses observed (figure 11.13). The effect of leaning back on reflexes evoked in EO and IO when tapping over the RA muscle is a reduction in amplitude. In contrast the effect of leaning back on reflexes evoked when tapping the EO and IO muscles are, when different, an increase in amplitude. A large increase in the size of the homonymous EO response (p<0.001) is the most obvious of these effects. For the majority of the other reflexes however, there was no significant difference in amplitude between the two positions. Overall therefore, the effect of leaning back on these reflexes is variable.
Figure 11.13. Comparison of the amplitudes of the long latency reflexes in the abdominal muscles when tapping rectus abdominis (RA), external oblique (EO) and internal oblique (IO) muscles in standing (u) and leaning back (L). (i – ipsilateral, cr – contralateral).
11.7 Summary of long latency reflexes in the abdominal and paraspinal muscles.

- Tapping on the RA muscle above the umbilicus evoked long latency reflexes of greater amplitude in the abdominal muscles than tapping on the EO and IO muscles. The reflexes in both IO muscles when tapping on the RA muscle were the only long latency effects to occur in all experiments undertaken. They were also the most potent long latency reflexes observed.

- For the majority of long latency reflexes observed there was no difference in the reflex amplitudes between ipsilateral and contralateral muscle pairs.

- The only long latency inhibitory reflexes observed were between the IO and LM muscles.

- The latencies of all 29 combinations occurred within a window of approximately 10ms.
In addition to the short latency reflexes evoked in the abdominal and paraspinal muscles, long latency reflexes in response to the same taps were also observed. These reflexes are widespread. In addition, the latencies of all these reflexes occur within a narrow time window between approximately 45 and 55ms after the tap is applied. These small differences in latency indicate that they may all share a common underlying pathway within the central nervous system. For the following discussion the assumption is initially made that all these reflexes involving both abdominal and paraspinal muscles are evoked via the same type of afferents and mediated by the same pathway within the central nervous system. Given the long latency of these reflexes, the number of different possible afferents and/or pathways within the central nervous system which may underlie these responses is extensive.

12.1 Spinally mediated long latency reflexes.

The reflexes could be spinally mediated as for the shorter latency reflexes. This would be the case if the afferents were of smaller diameter and therefore of slower conduction velocity. Group II muscle afferents have been shown to contribute to long latency reflexes in human limb muscles (Matthews, 1989; Schieppati & Nardone, 1997) and cat neck (Anderson, 1977) and trunk muscles (Wada & Kanda, 2001). There are no other reports of group II afferents evoking reflex activity in trunk muscles. However, Matthews (1972) suggests that a tap as applied in this study would be unlikely to evoke substantial group II muscle afferent activity. Long latency reflexes evoked from
cutaneous afferents have also been identified in human limb muscles by the application of stretch on the skin overlying the muscle tapped, similar to the tap used in this study (Corden et al. 2000; Darton et al. 1985; Macefield et al. 1996). It is therefore possible that the long latency reflexes observed in this study may also be mediated by cutaneous afferents. Indeed cutaneous reflexes within the abdominal muscles have been studied in both cat (Chennells & Floyd, 1952; Wada et al. 1999) and man (Hagbarth & Kugelberg, 1958; Kugelberg & Hagbarth, 1958; Satomi et al. 1993; Teasdall & Magladery, 1959).

Chennells & Floyd (1952) identified short latency reflexes from stimulating the cutaneous branches of the lower thoracic and upper lumbar nerves in the external and internal oblique muscles in the cat, but these were not of long latency. Wada et al. (1999) have also identified reflex activity in the trunk muscles from cutaneous afferents in the cat hind limb, but these were also of short latency. Short latency reflexes in human trunk muscles in response to stimulation of cutaneous afferents in the trunk by electrical stimulation, have been identified by Kugelberg & Hagbarth (1958) and Satomi et al. (1993). Such short latency reflexes have also been identified in response to a controlled scratch of the abdominal wall by Teasdall & Magladery (1959) and Satomi et al. (1993). Gibbs et al. (1995), even identified long latency reflex excitation in ES in response to cutaneous stimulation of the toe on the same side. Only Satomi et al. (1993) have identified longer latency reflexes in the abdominal muscles evoked by electrical stimulation of trunk muscle afferents. These were widespread being observed in the abdominal muscle of both sides even when the stimulus was applied unilaterally. However, the electrical stimulation applied by these authors (Satomi et al. 1993) was at high threshold levels and induced pain. These responses may therefore involve afferents from nociceptors. In addition, the latency of these later responses was about 90ms, whilst the early responses they report are at a latency of 30ms. Neither of these correspond to the latencies of either the short or long latency responses evoked in the
present study. Therefore, whilst cutaneous afferents are known to produce reflex effects in abdominal muscles, long latency reflexes evoked from these afferents have only been identified at high threshold. This is dissimilar to the non-noxious taps applied in this study, and at even longer latencies.

12.2 Long latency reflexes involving supraspinal pathways.

Alternatively, the pathway of the long latency reflexes may involve faster conducting muscle or cutaneous afferents, which evoke responses via ascending pathways to supraspinal centres, and descending pathways to the motoneurones. The most thoroughly investigated of these is the transcortical route (Thilmann et al. 1991; Matthews, 1991; Wiesendanger et al. 1975; Marsden et al. 1973). However, bearing in mind the postural function of the trunk muscles and the known involvement of brain stem nuclei in their control, (Kuypers, 1981; Lawrence & Kuypers, 1968a; Lawrence & Kuypers, 1968b) these subcortical brain stem regions may also be involved in these reflexes. The present study has only identified that these pathways exist and are widespread, but has not demonstrated which afferents or which parts of the central nervous system other than the spinal cord are involved. Long latency reflexes evoked from both cutaneous afferents (Evans et al. 1989; Evans et al. 1990; Evans et al. 1991; Gibbs et al. 1995) and muscle afferents (reviewed by Matthews 1991, see also Macefield et al. 1996) and have been shown to involve transcortical pathways. Whether either of these contributes to the long latency reflexes in human trunk muscles is yet to be determined.
12.3 Widespread long latency reflexes evoked by muscle afferent activity.

Both excitatory and inhibitory long latency reflexes in response to stretch in one muscle, have been observed in not only the muscle stretched, but also in muscles which may act as synergists or antagonists during different tasks (Gielen et al. 1988). These long latency effects were evoked from muscle afferents similar to the reflexes seen in the present study. In addition, the latencies of the responses identified in this study are only slightly shorter than those reported in the RA and ES muscles during perturbation of a supporting surface (Henry et al. 1998; Henry et al. 2001; Horak & Nashner, 1986; Keshner et al. 1988). Whilst these responses are thought to be evoked from afferents within muscles, these afferents are probably situated in the leg rather than the trunk. The reaction of the trunk muscles to release of loads being held by these trunk muscles, also occur at latencies only slightly longer than 50ms (Radebold et al. 2000; Radebold et al. 2001). These responses are most likely to be evoked by muscle afferents situated in the trunk muscles. There is therefore evidence to support the role of muscle afferents in evoking the widespread long latency responses seen in trunk muscles.

12.4 Contradictory and reciprocal patterns of short and long latency reflexes in the trunk muscles.

The inhibitory short latency and excitatory long latency responses seen in the IC and LM muscles in this study, and in ES (Zedka et al. 1999), may indicate that different afferents are responsible for short and long latency reflexes. The tapper used in this study will stretch not only the muscle afferents but also the cutaneous afferents in the skin under the tapper. The short latency excitation is most likely to be evoked by the muscle afferents, whereas the more widespread long latency excitation may be evoked
by the cutaneous afferents. If this is so, the longer latency responses in the IC and LM muscles of both sides may provide protection for the underlying structures, whereas the short latency reflexes induced by muscle afferents may be a response to movement, sensed within the muscles.

The pattern of long latency reciprocal inhibition and excitation between the LM and IO muscles is similar to that seen between trunk flexor and extensor muscles at shorter latency by Kugelberg & Hagbarth (1958). Using unpleasant levels of electrical stimulation these authors observed excitatory responses in the muscles directly under the stimulation and inhibition in the muscles on the opposite aspect of the trunk. They interpreted this pattern of response as being protective due to the unpleasant or noxious levels of stimulation required to evoke them. These effects seem likely to be evoked by cutaneous afferents, and could therefore be involved in the reciprocal inhibition and excitation seen at longer latency in the present study. However, the more innocuous levels of stimulation used in this study by tapping on the skin, have not previously been shown to produce such a response, neither has reciprocal inhibition evoked from cutaneous afferents been seen at longer latencies (cf. Leonard et al. 1999).

12.5 Long latency reflexes between the abdominal muscles.
That a response in the IO muscles from tapping the RA muscle always occurs and is the most potent of the long latency responses, suggests that the reflex control of the IO muscle is once again important, as it is at short latencies. This muscle is positioned not only to stabilise the pelvis and trunk, but is also ideally suited to brace the abdominal wall. Whilst stabilising the pelvis and trunk seems most likely to be evoked by muscle afferents, bracing the abdominal wall may be a form of protection for the abdominal contents, evoked via cutaneous afferents.
Unfortunately, leaning back did not produce similar changes in the amplitude of all reflexes between the abdominal muscles, when compared to the same reflexes evoked in standing. The reason for the reduction in size of the responses from RA afferents when leaning back is not obvious. In contrast, the increase in size of the responses when tapping is perhaps more easily explained, as voluntary activity of a muscle is known to increase the size of the longer latency responses to stretch within that muscle (Rothwell et al. 1980).

The increase in amplitude of the long latency responses evoked in ilO and crI0 when leaning back may be as a result of the smaller amplitude of the short latency reflexes in these muscles under the same conditions. When leaning back the degree of refractoriness (silent period) in these muscles after the smaller short latency responses, is likely to be less than after the short latency responses of far greater amplitude evoked when in standing. In this state when the refractory period of the IO motoneurones will be less extensive the arrival of the afferent activity at the motoneurones at approximately 50ms is more likely to bring them to threshold.

12.6 Could different long latency reflexes be evoked by different mechanisms?

The preceding discussion is based upon the assumption that all the responses identified within this study utilise the same pathway within the peripheral and central nervous systems. The similar pattern of the responses in all the muscles, and particularly the similar latencies supports this assumption. Even so the evidence is incomplete, and alternate explanations based on studies of the long latency reflexes in the limb muscles, are possible. Firstly, both muscle and cutaneous afferents have been shown to
contribute to long latency reflexes in the first dorsal interosseous muscle (Macefield et al. 1996). Long latency reflexes in distal and more proximally positioned muscles of the upper limb have been demonstrated to be evoked from different afferents, as have those in different muscles of the upper and lower limbs (Thilmann et al. 1991). Whether these variations in the origins of the long latency reflexes in the periphery are reflected in the trunk muscles remains unclear. Finally, Newsom Davis & Sears (1970) observed a long latency excitation following a short latency inhibition in the intercostal muscles, in response to an increase in load in the same muscle. Whilst not ruling out a long loop transcortical pathway, their favoured conclusion is that the long latency excitation was evoked by the Ia afferents. The longer latency in this instance was thought to be due to a stronger effect of autogenetic inhibition of the Ib afferents from the tendon organs within these muscles at short latency, overriding the excitatory effect of the Ia afferents. These muscles are axial and therefore relevant for the current study, and this particular control mechanism is thought to be related to the fine control involved in phonation. Even though the abdominal muscles are also known to be involved in phonation the same effect within one muscle has not been demonstrated in the current study, although the methods of investigation of the two studies are not directly comparable.
13 SUMMARY, CONCLUSIONS AND PROPOSALS FOR FURTHER STUDY.

This thesis details an investigation of the reflex control of human trunk muscles. The experimental protocol involved tapping the muscles with a mechanical device and detecting the resultant reflex activity by surface recording electrodes. The muscles studied were the rectus abdominis (RA), external oblique (EO) and internal oblique (IO) in the abdomen and the iliocostalis lumborum (IC) and the lumbar multifidus (LM) of the paraspinal muscle group. Both homonymous and heteronymous short latency and long latency reflexes were observed in all muscles.

Short latency reflexes were observed between all the abdominal muscles studied and were exclusively excitatory. The most potent responses were evoked by IO muscle afferents and evoked in the IO muscles. The responses involving the EO afferents and muscles were the next most potent, with those involving RA afferents and muscles being the least effective. The reflexes in the iIO and crIO from IO afferents were of large amplitude, and the difference in the latencies of these two reflexes was minimal. In fact the amplitudes of the iIO and crIO reflexes were comparable. The same was true of the amplitudes of the reflexes in iEO and crEO from IO afferents, and the amplitudes of the reflexes in iRA and crRA from IO afferents. In addition there was also minimal difference in the latencies of the ipsilateral and contralateral reflexes in EO and RA from IO afferents. These factors indicate that the crossed reflexes in IO, EO and RA from IO afferents are monosynaptic. The reflexes evoked in the paraspinal muscles were, in contrast to those in the abdominal muscles, excitatory ipsilaterally, and when present contralaterally, inhibitory. The latency of the crossed inhibition was longer than would be expected for a disynaptic pathway. Short latency reflexes between the IO and
LM muscles in both directions were observed less frequently and when present were small.

The long latency reflexes observed in the abdominal muscles were excitatory complimenting the short latency responses in these muscles. The reflexes in both IO muscles to tapping the RA muscle were always present and were the most potent reflexes observed. This mirrors the receptive nature of the IO muscles at short latency to afferent activity from IO and EO. The long latency reflexes between the paraspinal muscles were excitatory to both sides, in contrast to the short latency effects in the same muscles. The reflexes between LM and IO at longer latency were predominantly inhibitory. The current study has not identified the nature of the pathway of the long latency responses.

The findings of this study confirm previous biomechanical and EMG studies, which have shown that the abdominal muscles of both sides act together, most probably to stabilise the trunk. In addition, the strength of the reflexes between the iliO and crIIO muscles situated low down in the abdomen indicates that these muscles have a role in stabilising the pelvis. The more diverse activation patterns of the paraspinal muscles on either side during different tasks may require control predominantly from higher centres. This may explain the less potent contralateral reflexes between these muscles. Co-activation of the abdominal and paraspinal muscles is not frequently reported and this would explain the lack of short latency reflex connections between IO and LM.

These results raise certain questions regarding the reflex control of the trunk muscles. It is unknown if the short latency reflex connections to the more deeply situated TrA muscle are as extensive as those to IO. The fan shape of the upper, middle and lower
fibres of IO may indicate different functions for the different parts of this muscle. If so then the reflex connections to these different parts of the IO may differ. Whether this is so also remains to be seen. Whether the left and right transversus abdominis (TrA) muscles are connected by excitatory reflex pathways, remains to be ascertained. Similarly whether such reflex connections exist between the unisegmental fibres of LM, which have been proposed to co-activate stabilise the vertebral column (Richardson et al. 1999) remains to be seen. Trontelj et al. (1979) have previously identified reciprocal reflex responses in the deep and superficial parts of the erector spinae to tapping the vertebral column during different functional tasks. This pattern may be reflected in other reflex pathways. All these questions regarding the deeper muscles of the trunk arising from this study could be investigated using fine wire recording electrodes inserted into TrA, IO and LM.

With regards to the long latency reflexes between the trunk muscles there is a lack of clarity concerning the afferents and pathways within the central nervous system, which underlie these reflexes. Perturbation studies reveal reflexes in trunk muscles with latencies similar to those observed in this study. This may indicate a role for muscle afferents in evoking responses at this latency. To investigate this, anaesthetic block of the skin area where the tapper is applied could be used to eliminate cutaneous afferent activity whilst applying taps. However, application of such a blocking agent would need to completely block the cutaneous afferent activity to isolate the afferent activity to the muscle afferents. Unfortunately electrical stimulation on the trunk cannot definitively differentiate between reflexes evoked by cutaneous and muscle afferents. Whether these long latency reflexes have a transcortical loop is perhaps more amenable to investigation by using transcranial magnetic stimulation to condition the longer latency reflexes evoked by tapping (Chen et al. 1998; Rothwell, 1999).
It also remains to be seen if any of these reflex connections described are altered in pathological situations. The results presented in chapter 10 reveal a consistent asymmetry in the potency of the muscle afferent connections to the IO muscle of one side in a small number of subjects. That one of these subjects has a known scoliosis, makes this group of patients an obvious choice for further investigation. In addition, subjects with low back pain and particularly unilateral back pain, with or without neurological deficit on the side of the pain, would also be worthy of study. Indeed acute experimental pain has been shown to alter reflex activity in some muscle groups (Matre et al. 1998; Wang et al. 2000; Wang et al. 2001) but was shown to have no effect on the erector spinae muscle stretch reflex (Zedka et al. 1999). The effect of pain on the reflex activity in the abdominal muscles remains to be elucidated. Finally, subjects with unilateral central nervous system lesions such as a stroke may also exhibit differences in the control of these muscles, particularly in unilateral lesions such as a cerebral vascular accident.
14 APPENDIX.

14.1 Possible cross talk between electrodes.

One aspect of the study which may have affected the analysis, is whether surface electrodes record EMG not only from the underlying muscle but also record EMG from adjacent muscles (cross talk). Fuglevand et al. (1992) modelled the degree of cross talk at different distances and depths of a muscle being recorded from. For the optimal inter-electrode distance per pair of electrodes of 20mm, the model suggests that 90% of the EMG signal energy is dissipated at distances less than 12mm. It also suggests that 99% of the signal is dissipated at a distance of 18mm from the electrodes. The muscles most likely to be affected by cross talk in the present study are the homologous RA muscles and the homologous LM muscles. However, the difference between the electrode positions for these two muscles was in both instances at least 50mm in all cases. This is more than double the distance at which 99% of the signal would have been dissipated. It therefore seems unlikely that cross talk contributed to these recordings.

However, to confirm that this was not the case two examples illustrating the unique nature of the data collected by each pair of electrodes are shown in figures 14.1 and 14.2. In figure 14.1, average reflex responses in left and right RA muscles to tapping each muscle in turn are shown. In both experiments long latency reflexes are apparent in both muscles. In subject one when tapping the left RA there are obvious short and long latency reflexes in both RA muscles. However, in subject two whilst there are long latency reflexes in both muscles there is no short latency reflex in the crRA.
Figure 14.1. The effect of tapping left and right RA muscles and recording the reflex responses in both RA muscles in two different subjects. In the first example all data occurs at approximately the same time in each muscle, but in the second whilst the long latency responses occur simultaneously there is no short latency response in the contralateral muscle. This highlights that the responses in the contralateral muscles are most likely to be EMG activity from the underlying muscle and not cross talk.

The lack of a short latency reflex in the crRA when a reflex is so obvious in iRA, indicates that cross talk is an unlikely source of the signal in the crRA muscle.
Figure 14.2. a) Average and b) individual sweep data from left and right lumbar multifidus (LM) muscles collected simultaneously. a) The average of 30 sweeps, shown in non-rectified format (upper two traces) and rectified (lower two traces). In each case the ipsilateral LM is the bottom trace of the two and the contralateral LM is the top trace. b) Selected individual sweeps whilst showing some examples of similar EMG activity between the two waveforms, (b4 late responses & b5 early responses) also show other examples of obviously different EMG activity occurring at the same time (b1 late responses, b2 early responses, b3, early responses and b5 late responses). This suggests that the majority of the data collected from the electrodes positioned over the two lumbar multifidus muscles reflects activity from within each muscle and is not common to both sets of electrodes.

Evidence against any possible cross talk between the homologous LM muscles is also shown in figure 14.2. The average short and long latency reflex waveforms of two LM muscles are illustrated in a). Similar reflex waveforms and latencies are apparent particularly in the non-rectified traces. To emphasise that the signals are predominantly
from two different sources, five simultaneously recorded individual sweeps are superimposed and presented in b). Obvious differences between the two signals are shown in traces b1, b2 & b5, whilst similarities between the two waveforms are shown in b3 & b4. In the light of the obvious differences highlighted, the common signals seem more likely to be due to a common firing pattern of the motoneurones in the left and right muscles, rather than from cross talk.
LIST OF PUBLICATIONS


Kassem, I. & Evinger, L. C. Do humans exhibit eyelid dominance? (2001). *Society for Neuroscience abstracts*


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