Neurodynamic evaluation of the sciatic nerve during neural mobilisation: ultrasound imaging assessment of sciatic nerve movement and the clinical implications for treatment

Richard F. Ellis

A thesis submitted to AUT University in fulfilment of the requirements for the degree of Doctor of Philosophy (PhD)

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Department of Physiotherapy

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Declaration of Co-authored works

All the co-authors on the chapters/papers indicated in the following table have approved these for inclusion in Richard Ellis' doctoral thesis.

Chapter Three and Appendix Nine. Ellis, R. F., & Hing, W. A. (2008). Neural mobilization: a systematic review of randomized controlled trials with an analysis of therapeutic efficacy. *Journal of Manual & Manipulative Therapy, 16*(1), 8-22.	RE=85%, WH=15%
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Ellis, R., & Hing, W. (2009). Neurale mobilisation: Systematischer review randomisierter kontrollierter studien mit einer analyse der therapeutischen wirksamkeit. *Manuelletherapie, 2,* 47-57.	RE=85%, WH=15%
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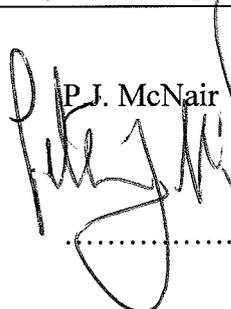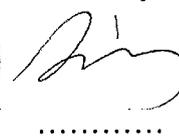
Publications and conference presentations

PUBLISHED PEER-REVIEWED ARTICLES.

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Ellis, R. F., Hing, W. A., Dilley, A., & McNair, P. (2008). Reliability of measuring sciatic and tibial nerve movement with diagnostic ultrasound during a neural mobilisation technique. *Ultrasound in Medicine and Biology, 34*(8), 1209-1216.

Ellis, R. F., & Hing, W. A. (2008). Neural mobilization: A systematic review of randomized controlled trials with an analysis of therapeutic efficacy. [Mobilizacje struktur nerwowych – przegląd systematyczny badań z randomizacją i grupą kontrolną oraz analiza skuteczności terapeutycznej]. *Medical Rehabilitation. [Rehabilitacja Medyczna], 12*(2), 34-44.

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Ellis, R. F., Hing, W. A., Mawston, G. & McNair, P. J. (2012). *In-vivo* ultrasound assessment of sciatic nerve excursion during neural mobilisation involving knee and ankle movement and the influence of cervical flexion. *Journal of Manual and Manipulative Therapy*.

Ellis, R. F., Hing, W. A., & McNair, P. J. (2012). Identifying the sequence of sciatic nerve excursion during different neural mobilisation exercises: an *in-vivo* study utilising ultrasound imaging. *Clinical Biomechanics*

CONFERENCE PRESENTATIONS.

The presenter is bolded.

Hing, W.A., & Ellis, R.F. (2006). *Neural tissue mobility measurement by diagnostic ultrasound.* Paper presented at the meeting of the 2nd Indian National Manual Therapy Conference., New Delhi, India.

Hing, W., & Ellis, R. (2007). *Diagnostic ultrasound assessment of sciatic nerve movement during neural mobilisation.* Paper presented at the meeting of the 15th International World Confederation of Physical Therapy (WCPT) Congress, Vancouver, Canada.

Ellis, R.F., Hing, W.A., & Allen, S. (2007). *Diagnostic ultrasound assessment of sciatic nerve movement during neural mobilisation - quantitative assessment and reliability.* Paper presented at the meeting of the New Zealand Manipulative Physiotherapists Association (NZMPA) Biennial Scientific Conference, Rotorua, New Zealand.

Ellis, R. F., & Hing, W. A. (2008). *Measurement of sciatic nerve movement, using ultrasound imaging, in a neural pre-loaded sitting position compared to an unloaded prone position.* Paper presented at the meeting of the International Federation of Orthopaedic Manipulative Physical Therapists (IFOMPT) Conference, Rotterdam, The Netherlands.

Ellis, R.F., Hing, W.A., & McNair, P.J. (2008). *Measurement of sciatic nerve movement, using ultrasound imaging, in a neural pre-loaded sitting position compared to an unloaded prone position.* Paper presented at the meeting of the Physiotherapy New Zealand (PNZ) Conference, Dunedin, New Zealand.

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Ellis, R. F., Milne, A., Tuck, K., Hing, W. A., & McNair, P. (2009). *The reliability of measuring knee range of movement in response to submaximal pain created by increased neural tension during a modified slump test.* Paper presented at the meeting of the New Zealand Manipulative Physiotherapists Association (NZMPA) Biennial Conference, Rotorua, New Zealand.

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Abstract

Neural mobilisation is a physiotherapeutic tool that is used to directly influence peripheral nerve mechanics, in particular the neurodynamic features of the peripheral nervous system. Neurodynamics refers to the integrated biomechanical and neurophysiological features of the nervous system. It is believed that many common peripheral nerve disorders have underlying features of neurodynamic dysfunction as part of their clinical aetiology, for example a loss of the ability of a nerve to glide and slide against adjacent tissues. Neural mobilisation offers an intervention which aims to restore optimal neurodynamics.

The first aim of this thesis was to collate the randomised controlled trials (RCTs) that have assessed neural mobilisation in order to evaluate the methods and strength of evidence of their findings. A systematic review was conducted which also focused on identifying methodological robustness and consistencies. Prior to this systematic review, there has been no previous systematic review published that has examined neural mobilisation. The results showed that there was a lack of RCTs that have assessed the therapeutic efficacy of neural mobilisations, particularly for neural mobilisation employed for lower limb nerve disorders. Secondly, the studies that were identified lacked consistency and had methodological weaknesses. None of these studies directly assessed nerve movement.

One of many issues apparent from the review was the lack of research which has utilised a tool that examines and quantifies the biomechanical features of peripheral nerve movement during neural mobilisation. This issue could be resolved through ultrasound imaging (USI) allowing real-time, *in-vivo* assessment of peripheral nerve mechanics. An initial aim of this thesis was to investigate the intra-rater reliability of

using USI to quantify sciatic nerve movement during neural mobilisation. Although the reliability of this technique has been assessed within the upper limb (median nerve), this has not been done for nerves of the lower limb. The findings of the reliability studies of this thesis indicated that there was excellent reliability (Intraclass Correlation Coefficient (ICC) $\geq$ 0.75) in the assessment of longitudinal sciatic nerve excursion which is consistent with previous studies which examined upper limb nerves.

The next study examined whether different types of neural mobilisation resulted in different amounts of sciatic nerve excursion. Theoretically different neural mobilisation exercises will influence nerve excursion differently, and this has been determined for the median nerve. However, this situation has not been explored in the lower limb. It was found that neural mobilisation exercises designed to maximise nerve excursion ('sliders') resulted in significantly greater nerve excursion compared to those exercises designed to elongate peripheral nerves ('tensioners'). This finding was consistent with studies conducted in the upper limb. These findings have important clinical ramifications as identifying which neural mobilisation exercises maximise nerve excursion will guide exercise selection.

The final two studies examined the two specific biomechanical features of sciatic nerve excursion during neural mobilisation, namely the influence of added nerve tension and the sequence of nerve excursion. Several key features were observed. Firstly, that sciatic nerve excursion was greatest when closer to the axis of joint rotation which induced the movement. Secondly, that additional neural tension, obtained from adding cervical flexion to the slump-sitting neural mobilisation exercises, was insufficient to alter sciatic nerve excursion consistently. Thirdly, that sciatic nerve excursion shows a specific sigmoidal sequence of excursion. These findings provided a

biomechanical perspective to support both theoretical models regarding nerve movement and clinical commentary concerning the use of neural mobilisation.

The findings of this thesis are relevant for the future design of clinical trials which will further examine the therapeutic efficacy of neural mobilisation. USI, as a tool to assess nerve movement *in-vivo* and real-time, is reliable and will enhance assessment of nerve mechanics in nerve disorders. Its use as an outcome measure for clinical trials is warranted. The design and choice of neural mobilisation exercises to influence nerve excursion can now be more specific. Ultimately this will allow more accurate assessment of the therapeutic efficacy of neural mobilisation.

Chapter One. Introduction

1.1 BACKGROUND

It has been theorised that adverse nerve mechanics has a significant role in many peripheral neuropathies, with impaired peripheral nerve movement having been implicated (Dilley, Odeyinde, Greening, & Lynn, 2008; Erel et al., 2003; Greening, Dilley, & Lynn, 2005; Greening et al., 2001; Greening et al., 1999; Hough, Moore, & Jones, 2007a; Nakamichi & Tachibana, 1995; Rozmaryn et al., 1998; Szabo, Bay, Sharkey, & Gaut, 1994; Wilgis & Murphy, 1986). Subsequently, neural mobilisation has emerged as a means of improving nerve movement. Neural mobilisation, which describes therapeutic exercises designed to influence peripheral nerve mechanics and physiology, initially focused at mitigating the effects of adverse neural tension (Shacklock, 2005b). However since the mid-1980's more theoretical perspectives of how neural mobilisation may be clinically beneficial have emerged. Subsequently a new term, *neurodynamics* (Shacklock, 1995b) was promoted.

A key premise of neurodynamics is the interdependent relationship between nerve mechanics and nerve physiology (Shacklock, 1995a, 2005a). Contemporary views regarding the use of neural mobilisation reflect the ability to influence nerve mechanics in order to reduce extrinsic and intrinsic mechanical pressures (Bertolini, Silva, Trindade, Ciena, & Carvalho, 2009; Brown et al., 2011; Butler, 2000; Butler, Shacklock, & Slater, 1994; Gifford, 1998; Herrington, 2006; Kitteringham, 1996; Shacklock, 2005a).

Initially, much of the evidence to support the use of neural mobilisation was anecdotal (Medina McKeon & Yancosek, 2008). To date, many of the perceived

benefits of neural mobilisation are founded in theory and have not been directly supported with research evidence (Beneciuk, Bishop, & George, 2009).

Much of the research to date that has examined neural mobilisation has used measures of clinical improvement (i.e. pain scales, joint range of movement (ROM), functional outcomes measures, etc.) in order to judge efficacy and provide validation that neural mobilisation can directly influence peripheral nerves. Furthermore, the initial studies that have examined the influence of neural mobilisation on nerve movement were conducted using cadavers (Coppieters & Alshami, 2007; Coppieters & Butler, 2008). However, such studies had a limited scope for providing support for theoretical concepts regarding nerve mechanics due to the limitations of cadaveric research.

As most of the early concepts of neurodynamics and neural mobilisation were based on theory and cadaveric research primarily, the specific exercises utilised in the early clinical trials were chosen without a sound basis having been provided by *in-vivo* experimental studies. In fact several authors (Akalin et al., 2002; Bardak et al., 2009; Baysal et al., 2006; Heebner & Roddey, 2008; Pinar, Enhos, Ada, & Gungor, 2005) stated that the neural mobilisation exercises utilised in their studies were chosen based on those used in previous research.

With the rapid development of modern imaging techniques, it has been possible to assess peripheral nerve mechanics both *in-vivo* in humans and real-time. Ultrasound imaging (USI) provides an effective, low risk and low cost method of real-time assessment of nerve mechanics. USI analysis therefore provides an accessible research tool to enable the systematic assessment of neural mobilisation techniques that are designed and utilised to deliberately manipulate and exploit nerve movement (Hough, Moore, & Jones, 2000b). This has lead to studies which have specifically examined the

influence of neural mobilisation upon upper limb nerve mechanics with USI (Coppieters, Hough, & Dilley, 2009; Echigo et al., 2008). Different types of neural mobilisation exercises have been examined in the upper limb. For example, techniques to enhance nerve sliding have been shown to produce more median nerve excursion compared to tensioning techniques (Coppieters et al., 2009).

However, the fact that upper limb nerves were the initial focus, further research is required for lower limb nerves to explore whether the findings seen within the upper limb are apparent in the lower limb. Caution must be made when making inferences regarding lower limb nerve mechanics from studies conducted in the upper limb. The kinematics and functional use of the upper compared to lower limbs is very different. To date, there is no research that has analysed lower limb nerve movement *in-vivo* in humans in response to neural mobilisation.

Therefore, the intention of this thesis was to examine sciatic nerve mechanics in healthy participants. *In-vivo* analysis of nerve mechanics in humans' is in its infancy. Before this field of research can be expanded into clinical populations, it is imperative to initially assess normal sciatic nerve mechanics in response to neural mobilisation. This thesis provides a series of studies that have addressed the issues raised above, with specific reference to the lower limb and with an overall aim to provide experimental evidence to support or refute the theoretical concepts concerning neural mobilisation.

1.2 AIMS AND OBJECTIVES OF THIS DOCTORAL RESEARCH

The aims of this research were:

(1) To collate the research that has been conducted regarding the use of neural mobilisation in order to assess randomised controlled trials (RCTs) that

have examined the therapeutic efficacy of neural mobilisation and evaluate the strength of evidence to support the use of neural mobilisation. A systematic review of RCTs was conducted to examine the available clinical research regarding neural mobilisation.

(2) To investigate the reliability of using USI to quantify sciatic nerve excursion during mobilisation exercises. Two intra-rater reliability studies were conducted, using USI and frame-by-frame cross-correlation analysis, to quantify sciatic nerve movement during a slump-sitting neural mobilisation exercise and a side-lying neural mobilisation exercise.

(3) To investigate whether different types of neural mobilisation exercises result in different amounts of sciatic nerve excursion. Specific analysis of the amount of sciatic nerve excursion was conducted during different types of neural mobilisation exercises.

(4) To investigate whether different biomechanical features (the proximity of joint movement, additional neural tension and sequence of nerve excursion) varied in respect to sciatic nerve excursion in response to slump-sitting neural mobilisation exercises.

1.3 SIGNIFICANCE OF THIS DOCTORAL RESEARCH

The findings from this research have significance for professionals who are involved in the prevention and management of peripheral nerve disorders, particularly those affecting the sciatic nerve and its associated nerve tracts. Information from this research will increase understanding of the amount of sciatic nerve excursion that can be expected in healthy people in response to neural mobilisation exercises.

Furthermore, the amount of sciatic nerve excursion during different types of neural mobilisation exercises (i.e. sliders and tensioners) will allow more specific and appropriate selection of neural mobilisation exercises. In addition to improved exercise selection, enhanced understanding of sciatic nerve biomechanics, in response to slump-sitting neural mobilisation, will provide clinicians' greater knowledge of biomechanical effects associated with the movement of nerves in the lower limb.

1.4 THESIS PRESENTATION

This thesis is presented in a paper based style. Initially a general and narrative literature review discusses the relevant background regarding neurodynamics, the different neurodynamic and biomechanical features of the peripheral nervous system (PNS) and the clinical implication of impaired nerve movement, neural mobilisation and the use of USI to assess nerve motion. Thereafter the thesis is comprised of the following papers:

1. "Neural mobilisation: a systematic review of randomised controlled trials with an analysis of therapeutic efficacy" (Chapter Three).

2. "Reliability of measuring sciatic and tibial nerve movement with diagnostic ultrasound during a neural mobilisation technique" (Chapter Four).

3. "The influence of increased nerve tension on sciatic nerve excursion during a side-lying neural mobilisation exercise - a reliability study" (Chapter Five).

4. "Comparison of different neural mobilisation exercises upon longitudinal sciatic nerve movement: an *in-vivo* study utilising ultrasound imaging" (Chapter Six).

5. "*In-vivo* ultrasound assessment of sciatic nerve excursion during neural mobilisation involving knee and ankle movement and the influence of cervical flexion" (Chapter Seven).

6. "Identifying the sequence of sciatic nerve excursion during different neural mobilisation exercises: an *in-vivo* study utilising ultrasound imaging" (Chapter Nine).

Thereafter, a summary of the overall thesis is provided, conclusions are drawn and areas for future research are presented.

Chapter Two. Literature review

2.1 INTRODUCTION

Contemporary theories regarding the potential benefit of neural mobilisation reflect the likelihood that many different inter-related influences including biomechanical and neurophysiological effects occur. More specifically, there is a widely held belief that neural mobilisation can be used to enhance nerve movement for clinical nerve disorders where nerve movement is perceived to be impaired (Akalin et al., 2002; Bardak et al., 2009; Bialosky et al., 2009b; Brown et al., 2011; Coppieters & Alshami, 2007; Fahrni, 1966; George, 2002; González-Iglesias, Huijbregts, Fernández-de-las-Peñas, & Cleland, 2010; Kitteringham, 1996; Medina McKeon & Yancosek, 2008; Oskay et al., 2010; Pinar et al., 2005; Rozmaryn et al., 1998; Szabo et al., 1994). However, most of the clinical trials that have been conducted to assess the influence of neural mobilisation have not analysed their influence on nerve movement.

In spite of the fact that there are many different underlying mechanisms of neural mobilisation, it is the focus of the following literature review to evaluate the biomechanical features of the PNS that allows peripheral nerves to respond to body movement. Furthermore, the implications of impaired nerve movement are discussed. Contemporary theories and research evidence is discussed in regard to healthy and pathologic situations. Finally the background to the use of USI in the assessment of nerve movement is discussed. The detail within this literature review is important to create an understanding of the intent and objectives of this thesis.

2.2 NEURODYNAMIC FEATURES OF THE PERIPHERAL NERVOUS SYSTEM

2.2.1 Neurodynamics.

Scientists and medical professionals have been interested in the mechanical properties and function of the PNS since the late 1800's, beginning with discussion of clinical tests of neural tissue sensitivity such as the Laségue sign and the straight-leg raise (SLR) test (Dyck, 1984; Woodhall & Hayes, 1950). Impaired nerve motion was implicated in various clinical conditions and was described as 'adverse neural tension' (Breig, 1978).

Neurodynamics as a specific concept was presented in a seminal paper published in 1995 (Shacklock, 1995b). Neurodynamics refers to the integrated biomechanical, physiological and mechanical functions of the nervous system (Butler, 2000, 2005; Shacklock, 1995a, 1995b, 2005a; Walsh, 2005). The nervous system has a vital role as a bidirectional transport system carrying information to and from different body systems in order to perceive, process and activate human movement. In doing so, the nervous system must therefore be able to cope with the mechanical and physiological stresses that are imposed upon it from neighbouring tissues in order to operate effectively. Specialised interdependent neuroanatomical and neurophysiological features allow the nervous system to maintain optimum function.

"If it cannot move, glide and stretch, then the nervous system's cardinal function of conduction will be useless" (Butler, 2000, p.98). For a peripheral nerve to function properly it must maintain an undisturbed connection to neuronal cell bodies within the central nervous system and must also maintain a continuous blood supply (Lundborg, 1975). Therefore the PNS must simultaneously cope with body movement and dissipate

mechanical force by adapting to elongation and compression which allow independent movement in relation to its surrounding tissues.

To ensure that significant or adverse increases in neural tension are generally avoided, peripheral nerves are well designed to cope with movement and elongation (Bertelli, Tumilasci, Mira, & Loda, 1993; Dilley, Lynn, Greening, & DeLeon, 2003; Dilley, Summerhayes, & Lynn, 2007; Hall, Zusman, & Elvey, 1998; Kwan, Wall, Massie, & Garfin, 1992; Marshall, 1883; Sunderland, 1990). For example the toe-region of both the load-elongation and stress-strain curves for a peripheral nerve (Figure 1) suggest that there is an *in-situ* slack which allows a nerve initially to respond to elongation without a significant increase in resistance, force or stress. Further elongation results in a linear increase in force/stress until a time where the structural integrity of the nerve fails and permanent deformation occurs (Beel, Groswald, & Luttges, 1984; Kwan et al., 1992; Li & Shi, 2007; Rydevik et al., 1990; Topp & Boyd, 2006).

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Figure 1. Typical A) load-elongation & B) stress-strain curves for peripheral nerves
Topp & Boyd (2006). Structure and biomechanics of peripheral nerves: nerve responses to physical stresses and implications for physical therapist practice. *Physical Therapy, 86*(1), p. 101.

There are several essential neurodynamic features of the nervous system. It is essential to the development of this thesis to discuss the relevance of these neurodynamic features in order to understand neural movement and mechanics. Although it is easier to discuss each of the neurodynamic features in isolation, it is important to note that these features are interdependent.

2.2.1 The ability of a nerve to move and slide.

From an extrinsic perspective, the PNS must be able to move and slide in relation to, and independently of, its surrounding tissues (Butler, 2000; Butler & Gifford, 1989b; Dilley et al., 2003; Shacklock, 2005a). The relationship between the PNS and the surrounding tissues is commonly referred to as the 'mechanical interface' (Butler, 1989, 2000; Shacklock, 1995b, 2005a; Slater, Butler, & Shacklock, 1994). Although the mechanical interface, also known as the 'nerve bed' or 'neural container', is not a direct layer or feature of the specific anatomy of the PNS, it must be taken into account when discussing nerve biomechanics and nerve pathology.

Excursion of a nerve refers to the movement of a nerve in respect to the surrounding mechanical interface (Boyd, Puttlitz, Gan, & Topp, 2005; Byl, Puttlitz, Byl, Lotz, & Topp, 2002; Dilley et al., 2003; Erel et al., 2003; McLellan & Swash, 1976; Topp & Boyd, 2006). This sliding capacity allows the nerve to adapt to changes in position and length of the nerve bed imposed by limb movements (Abe, Doi, & Kawai, 2005; Dilley et al., 2007; Erel et al., 2003; McLellan & Swash, 1976; Szabo et al., 1994; Wilgis & Murphy, 1986).

It has been suggested that nerve excursion, in all planes, allows dissipation of tension in an attempt to equalise pressure along the length of the nerve tract (Breig & Troup, 1979b; Dilley et al., 2003; McLellan & Swash, 1976; Shacklock, 2005a; Szabo et al., 1994; Topp & Boyd, 2006; Walsh, 2005). Significant mechanical forces can be generated as peripheral nerves slide against the mechanical interface. For example, passive finger and wrist flexion has been shown to generate significant frictional forces from the flexor tendons relative to the median nerve (Szabo et al., 1994).

The routes of most peripheral nerve trunks fall beyond the movement plane of many joints (Beith, Robins, & Richards, 1995; Phillips, Smit, De Zoysa, Afoke, &

Brown, 2004). Dissipation of tensile forces via elongation and sliding must occur relatively evenly throughout the length of the nerve. Therefore theories suggest that if nerves are not able to slide freely then the portion of the nerve closest to the axis of joint movement has greater tensile forces imposed on it (Dilley et al., 2008; Erel et al., 2003; Greening et al., 2001; Hunter, 1991, 1996). The ability to slide may also protective against increases in intraneural pressure caused by excesses of tension (Butler, 2000; Dilley et al., 2003; McLellan, 1975; McLellan & Swash, 1976; Shacklock, 2005a; Szabo et al., 1994).

The neural connective tissue layers have specialised roles in facilitating nerve excursion. The mesoneurium is the external sheath, or adventitia, surrounding the whole nerve. This allows sliding of the nerve relative to the mechanical interface (Butler, 2000; George & Smith, 1996; Lundborg & Dahlin, 1996; Mackinnon, 2002; Rath & Millesi, 1990; Shacklock, 2005a). The external epineurium allows nerve sliding in relation to the mesoneurium and nerve bed (George & Smith, 1996; Mackinnon, 2002; Rydevik, Lundborg, Olmarker, & Myers, 2001).

Neural sliding is believed to also occur internally as the individual fascicles and fibres slide against each other (Abe et al., 2005; Butler, 1989; Shacklock, 2005a; Walsh, 2005). This internal movement is facilitated by the internal epineurium and endoneurium (Butler, 2000; Gifford, 1998; Millesi, Zoch, & Rath, 1990; Shacklock, 2005a; Walsh, 2005).

Movement of the nervous system also aids nerve nutrition and removal of metabolic wastes. Axoplasmic flow (otherwise known as axonal transport) exhibits thixotropic properties. Thixotropy refers to the decreased viscosity of a fluid (i.e. axoplasm) in response to movement (Baker, Ladds, & Rubinson, 1977; Coppieters, Bartholomeeusen, & Stappaerts, 2004; Shacklock, 2005a). For example, repeated

movement of neural tissue in relation to the local mechanical interface, or vice versa, may cause a decrease in the viscosity of axoplasm (Coppieters et al., 2004; Shacklock, 1995b, 2005a; Shacklock, Butler, & Slater, 1994). A 'milking effect' from nerve movement is believed to occur which will exploit the thixotropic properties therefore aiding axoplasmic flow, microcirculation (Akalin et al., 2002; Butler, 2000; Shacklock, 1995a, 2005a; Shacklock et al., 1994) and decreasing internal pressure within the nerve (Akalin et al., 2002; Baysal et al., 2006).

2.2.2 The ability of a nerve to withstand stretch.

The ability of the PNS to dissipate tensile load is critical to maintain nerve function (Coppieters et al., 2006; Phillips et al., 2004). As little as 5-10% increase in nerve strain has been shown to impair intraneural vascularity (Ogata & Naito, 1986), axoplasmic flow (Dahlin & McLean, 1986) and nerve conductance (Wall et al., 1992). As little as 3% increase in nerve strain, in an already neurogenically inflamed nerve, leads to ectopic nociceptive discharge and dyaesthetic pain (Dilley, Lynn, & Pang, 2005).

The neural connective tissue layers have an important role to play in nerve elongation. The collagen fibres of the epineurium and endoneurium have an undulating configuration which allows some slack to accommodate initial elongation forces (Marshall, 1883; Sunderland, 1965; Topp & Boyd, 2006). The perineurium provides the primary resistance to elongation/stretching (Bove, 2008; Kwan et al., 1992; Piña-Oviedo & Ortiz-Hidalgo, 2008; Rydevik et al., 1990; Sunderland, 1990; Sunderland & Bradley, 1961a). The perineurium can accept 18-22% strain before a peripheral nerve structurally fails (Rydevik et al., 1990; Sunderland & Bradley, 1961a). The spinal nerve roots do not have a perineurial layer and are therefore less resistant to elongation

compared to peripheral nerves (Singh, Kallakuri, Chen, & Cavanaugh, 2009; Sunderland, 1965; Sunderland & Bradley, 1961b).

The protective ability of the perineurium has been shown in animal studies which have deliberately induced an experimental neuritis. For instance, Dilley et al. (2005) provided evidence of a small number of A and C fibres of the sciatic or peroneal nerves in rats becoming mechanosensitive when exposed to elongation, in the presence of a local neuritis. The proportion of fibres which exhibited mechanosensitivity dramatically increased when a small cut was made in the perineurium. Although unsure of the precise mechanism, Dilley et al. (2005) commented upon the important protective role that the perineurium offered in response to mechanical load (i.e. stretch) under conditions of local neurogenic inflammation.

Like other soft tissues, the neural connective tissues possess viscoelastic properties (i.e. stress-relaxation, creep, etc.) which allow nerves to adapt to elongation forces (Abe et al., 2005; Kwan et al., 1992; Lundborg & Rydevik, 1973; Phillips et al., 2004; Sunderland & Bradley, 1961a; Wall, Kwan, Rydevik, Woo, & Garfin, 1991; Wall et al., 1992). A mixture of both elastin and collagen fibres throughout the connective tissue layers and the addition of a constant endoneurial fluid pressure contribute significantly to the viscoelasticity of peripheral nerves (Phillips et al., 2004).

The vasa nervorum are vast vascular networks throughout all connective tissue layers and capillary plexuses within each fascicle (Del Pinal & Taylor, 1990; Keir & Rempel, 2005; Kerns, 2008; Lundborg & Dahlin, 1996; Lundy-Ekman, 2002; Rydevik et al., 2001). The undulating and coiled course of these blood vessels allows maintenance of vessel lumen size, and therefore blood flow, in response to length and pressure changes during elongation (Bove, 2008; Bove & Light, 1997; Keir & Rempel,

2005; Kitteringham, 1996; Lundborg & Dahlin, 1996; Rempel, Dahlin, & Lundborg, 1999; Rempel & Diao, 2004).

It has been shown in animal studies, that as little as 8% elongation can cause a decrease in intraneural blood flow (Lundborg & Rydevik, 1973), and greater than 15% elongation can cause total stagnation of flow (Lundborg & Rydevik, 1973; Ogata & Naito, 1986; Wall et al., 1992). Similar levels of nerve elongation (15%) have been shown to result in a reduction of nerve root conductance (Rydevik, Brown, & Lundborg, 1984; Sunderland & Bradley, 1961b) with a link to impairment in intraneural microcirculation (Rydevik et al., 1984). It is the coiled path and viscoelastic nature of the connective tissues, of both the nerve and vasa nervorum, which allows rapid restoration of intraneural blood flow upon release of elongation forces (Keir & Rempel, 2005; Lundborg & Rydevik, 1973; Shacklock, 1995a).

Providing innervation to all neural connective tissue layers and the vasa nervorum are the nervi nervorum (Bove, 2008; Bove & Light, 1995, 1997; Gifford, 1998; Hall & Elvey, 1999; Marshall, 1883; Sauer, Bove, Averbeck, & Reeh, 1999). The nervi nervorum are unmyelinated nociceptors which are stimulated by excessive mechanical and chemical stress (Bove & Light, 1995, 1997; Hall & Elvey, 1999; Sauer et al., 1999). The nervi nervorum are mechanosensitive to elongation stress towards the natural limits of length of the neural connective tissues (Bove & Light, 1997; Dilley et al., 2005). Like the vasa nervorum, the nervi nervorum are coiled and undulating allowing enough slack through their course to accommodate nerve elongation (Bove & Light, 1997; George & Smith, 1996; Gifford, 1998; Kitteringham, 1996; Lundborg, 1975; Shacklock et al., 1994; Topp & Boyd, 2006).

2.2.3 The ability of a nerve to withstand compression.

Excessive compression may compromise neurophysiological features such as axoplasmic flow, impulse conduction and intraneural blood flow. Decreases in the cross-sectional area (CSA) of fibro-osseous tunnels (e.g. carpal tunnel and cubital tunnel) result in significant increases in extraneural pressures during normal movements of the wrist (Gelberman, Hergenroeder, & Hargens, 1981) and elbow (Gelberman et al., 1998). For instance, the ulnar nerve is reduced in size by 50% to accommodate a 50% reduction in the relative diameter of the ulnar groove at the elbow during movement (Apfelberg & Larson, 1973; Gelberman et al., 1998). Similarly, the spinal canal has been shown to reduce in diameter by 16% during spinal extension (Schonstrom, Lindahl, Willen, & Hansson, 1989).

Increases in carpal tunnel pressures of between 40-50mmHg have been shown to reduce the sensory and motor conductance of the median nerve by up to 40% (Gelberman, Szabo, Hargens, Yaru, & Minteer-Convery, 1983). Pressures as little as 30mmHg in the carpal tunnel have been shown to elicit signs of paraesthesia (Gelberman et al., 1981). Research by Gelberman et al. (1981) suggested that the pressure within the carpal tunnel of healthy humans rose from 3mmHg to 30mmHg (wrist in neutral) and 90-100mmHg (wrist in full flexion or extension) in humans with carpal tunnel syndrome (CTS) (Gelberman et al., 1981). Therefore, the necessity of the nervous system to accommodate compression, which is forced upon it by a decrease in the diameter of the surrounding mechanical interfaces, is vital.

The epineurium provides the primary resistance to compression (Bove & Light, 1997; Sunderland, 1990), acting as a shock-absorber to dissipate compressive forces (Rydevik, Lundborg, & Bagge, 1981; Sunderland, 1990). Both connective tissue density (Armstrong, Castelli, Evans, & Diaz-Perez, 1984; Keir & Rempel, 2005;

Rempel et al., 1999; Rydevik et al., 2001; Sunderland, 1965; Sunderland & Bradley, 1952) and fascicle numbers (Gifford, 1998; Mackinnon, 2002; Sladjana, Ivan, & Bratislav, 2008; Sunderland, 1965, 1990; Sunderland & Bradley, 1949) have been shown to be greater at regions of increased mechanical load, i.e. adjacent to a joint. Both of these situations afford the PNS greater protection from compressive forces due to the relative increase in connective tissue volume (Gifford, 1998; Mackinnon, 2002; Sladjana et al., 2008; Sunderland, 1965, 1990; Sunderland & Bradley, 1949).

Compressive forces, along with the associated increases in intraneural pressure, have the potential to mechanically occlude intraneural vessels. As the vasa nervorum form large plexuses and anastamoses throughout all structural levels of a peripheral nerve, local compression can cause focal ischaemia but may not necessarily have a profound influence on nerve conductance, at least in the short term (Lundborg, 1975; Olmarker, Holm, & Rydevik, 1990; Rydevik et al., 1991; Sunderland, 1990). For example, local epineurial venous blood flow in animals has been shown to be impaired at 20-30mmHg (Ogata & Naito, 1986; Rydevik et al., 1981), and total nerve ischaemia occurred at 60-80mmHg (Ogata & Naito, 1986; Rydevik et al., 1981). However, nerve conduction impairment was not seen until higher levels (75-100mmHg) of compression in studies in animals (Olmarker et al., 1990; Rydevik et al., 1991). The implication is that nerve conductance may be able to be maintained, in the short term at least, from the collateral and branching vascular networks beyond the region of compression (Lundborg, 1975; Olmarker et al., 1990; Rydevik et al., 1991; Sunderland, 1990).

As noted earlier, the nervi nervorum act as nociceptors in the presence of excessive mechanical stress (Bove & Light, 1995, 1997; Hall & Elvey, 1999; Sauer et al., 1999). Adverse nerve compression can be a key factor in the development of neurogenic inflammation and subsequently the potentiation of ectopic sensory discharge

(Butler, 1989; Cleland, Hunt, & Palmer, 2004; Devor, 1991; Kobayashi et al., 2009; Rydevik et al., 1984) and development of abnormal impulse generating sites (Butler, 2000; Devor, 1991). Some theories, however, suggest that adverse symptoms which are believed to result from focal compression may not solely be as a result of mechanosensitivity (Bove & Light, 1997; Greening, 2006). For example the nervi nervorum may become sensitised in the presence of intraneural oedema or intraneural ischaemia (Bove & Light, 1997; Dilley et al., 2005).

2.3 BIOMECHANICAL FEATURES OF NERVE EXCURSION

There are several important biomechanical features of the PNS that dictate the way it moves against the mechanical interface. It is important to acknowledge and understand the biomechanics of nerve movement when designing and prescribing neural mobilisation exercises. Historically, neural mobilisation exercises have been designed to target perceived neural tension or have been chosen, in some research trials, due to historical precedents. A key premise of this thesis is to explore several of these biomechanical features in order to have a better understanding of nerve movement during neural mobilisation.

2.3.1 The nervous system is a continuous system.

"The nervous system as a whole is a mechanically and physiologically continuous structure from the brain to the end terminals in the periphery" (Shacklock et al., 1994, p. 21). That the nervous system is a continual system is very important when considering the mechanical influences upon any region of the PNS can have mechanical and/or physiological consequences elsewhere in the system (Beel et al., 1984; Breig &

Marions, 1963; Butler, 1989, 2000; Elvey & Hall, 2004; Gifford, 1998; Shacklock, 1995b, 2005a; Shacklock et al., 1994; Smith, 1956; Walsh, 2005).

For example, from studies performed on rhesus monkeys and unembalmed full-term human foetuses it was observed that movement of the hip through flexion (with the knee extended and ankle dorsiflexed) induced excursion of the spinal cord distally, from traction imposed at the lumbosacral nerve roots, as far as the cerebellum (Smith, 1956). From his cadaver and biomechanical studies, Breig (1978) showed that movement of the cervical spine will influence movement at the lumbar dural sheath and vice versa. Caudad movement of the dural sheath, within the vertebral canal, and spinal nerve root has been shown in cadavers during SLR (Charnley, 1951; Falconer, McGeorge, & Begg, 1948; Goddard & Reid, 1965; Inman & Saunders, 1941; Shacklock, 2007) and in animals (Smith, 1956). Conversely, lumbar flexion will cause a cranial excursion of the lumbar nerve roots (Shacklock, 2007; Smith, 1956).

The fact that the nervous system is a continual system has important implications when considering assessment and treatment. Influence at one point in the nervous system can have influence at more distant locations, with quite important ramifications (Butler, 1989, 2000; Rydevik et al., 1984; Shacklock, 2005a).

2.3.2 The sequence of nerve excursion.

There is some evidence to suggest that nerve excursion follows a sigmoidal pattern. Following analysis of studies which have examined the viscoelastic properties (i.e. stress-strain, load-elongation relationships, etc.) of peripheral nerves per se, it has been suggested that a nerve initially goes through a period of unfolding followed by sliding, once the inherent slack of the nerve is taken up, which is followed by elongation as the elastic limits of the nerve is reached (Millesi, 1986; Topp & Boyd, 2006).

Depending on the position of a limb and therefore the position of the nerve bed, peripheral nerves and spinal nerve roots may be in unloaded positions, i.e. curled or curved (Breig & Marions, 1963; Dilley et al., 2003; Dilley et al., 2007; Ko et al., 2006; Sunderland, 1978), particularly those peripheral nerves that are situated on the concave aspect of a joint (Shacklock, 2005a). This unloading or slack represents what Dilley and colleagues have referred to as areas of high compliance (Dilley et al., 2003; Dilley et al., 2007). From a biomechanical perspective, compliance is the inverse of stiffness (Hall, Cacho, McNee, Riches, & Walsh, 2001; Walker & Cartwright, 2011). Stiffness is represented by the slope of the linear portion of a load-elongation curve (Topp & Boyd, 2006; Walker & Cartwright, 2011). The resting *in-situ* slack, as represented by the initial toe-region of a load-deformation curve (Rydevik et al., 1990; Topp & Boyd, 2006), is perhaps a more suitable term than compliance.

Close to large joints, which have large axes of rotation, significant nerve slack must exist (Dilley et al., 2003; Millesi, 1986; Phillips et al., 2004; Zoech, Reihsner, Beer, & Millesi, 1991). For example, longitudinal excursion of the median (Dilley et al., 2003) and ulnar (Dilley et al., 2007) nerves during abduction of the shoulder has shown very little movement within the first 50° of abduction. However, beyond 50° of abduction significantly greater median nerve excursion occured to allow the upper limb to come away from the body (Dilley et al., 2003).

More recently, Dilley and colleagues have also shown, with USI, that peripheral nerves that appear to be folded and slack at rest will straighten once exposed to joint movement and therefore elongation (Dilley et al., 2003; Dilley et al., 2007). A similar phenomenon has been observed during this doctoral research (Figure 2). Other areas of nerve slack have been described at the elbow (Dilley et al., 2003; Dilley et al., 2007), wrist (Wright, Glowczewskie, Wheeler, Miller, & Cowin, 1996) and hip (Charnley,

1951; Goddard & Reid, 1965; Inman & Saunders, 1941; Shacklock, 2005b, 2007).

Unfolding occurs at the many structural elements of a peripheral nerve including

individual axons, fascicles and the nerve trunk (Byl et al., 2002; Dilley et al., 2003;

Grewal, Varitimidis, Vardakas, Fu, & Sotereanos, 2000), before nerve sliding can occur

(Breig, 1978; Kwan et al., 1992; McLellan & Swash, 1976; Shacklock, 2005a;

Shacklock et al., 1994).
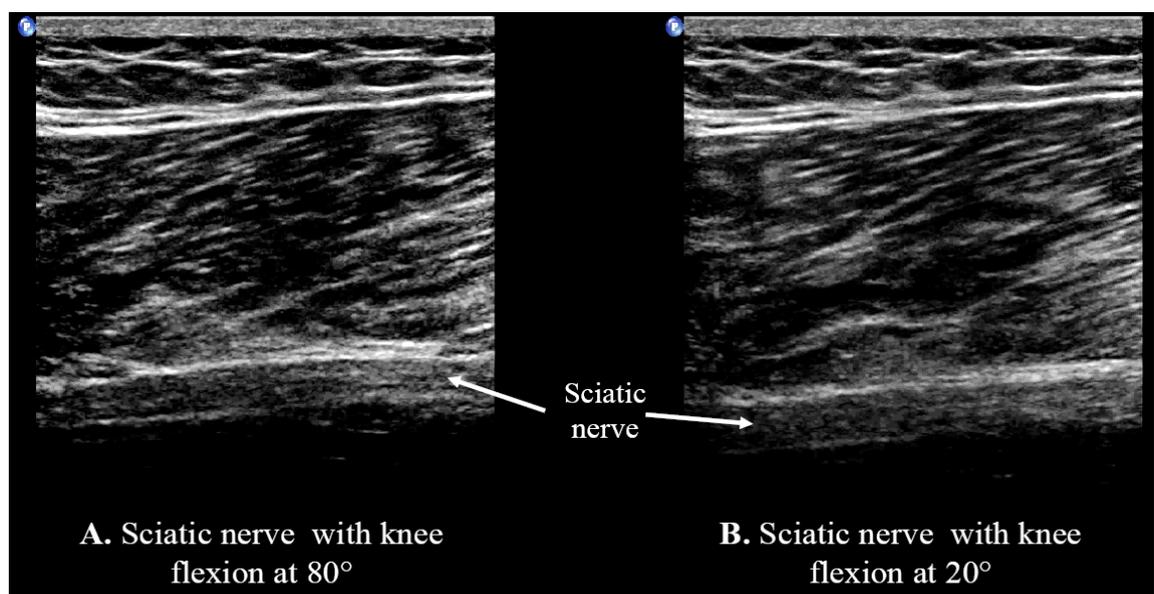
Figure 2. Sciatic nerve unfolding with passive knee extension
A) Curved sciatic nerve *in-situ*. B) Straight sciatic nerve following elongation as a result of knee extension. These images were taken at the level of the posterior mid-thigh and were collected as part of this doctoral research.

Following unfolding of the nerve and the respective connective tissue layers,

sliding and eventually elongation can occur (Breig, 1978; Kwan et al., 1992; Shacklock,

1995b, 2005a, 2007; Shacklock et al., 1994). As the slack of the neural connective

tissues is taken up, eventually there will be relatively less sliding and greater nerve

elongation (Charnley, 1951; Dilley et al., 2007; Kwan et al., 1992; McLellan & Swash,

1976; Shacklock, 1995b, 2005a; Topp & Boyd, 2006).

This sequence of nerve movement has been illustrated in several studies. Human cadaveric experiments have shown that during SLR excursion of the sciatic nerve initially started after some degree of hip flexion, which varied depending on which research is examined [for example after 5° of hip flexion (Goddard & Reid, 1965) or following 15-30º of hip flexion (Breig & Troup, 1979b; Charnley, 1951; Fahrni, 1966; Inman & Saunders, 1941)]. As the SLR continued, progressively less actual sliding occurred, so that by greater than 70° of hip flexion movement diminished and elongation occurred (Charnley, 1951; Gajdosik, LeVeau, & Bohannon, 1985; Gifford, 1998; Goddard & Reid, 1965; Shacklock, 2005a). A similar trend was seen by Ko et al. (2006) with excursion of the lumbosacral nerve roots during the SLR in cadavers. The nerve roots remained slack and still during the first 30-40° of hip flexion, then root excursion was evident with two-thirds having been completed at 60° hip flexion, and beyond 70° hip flexion excursion reduced and elongation was evident.

Different aspects of sequential nerve excursion have also been demonstrated with *in-vivo* analysis of the median nerve. For example, longitudinal median nerve excursion in the upper arm, induced by extension of the wrist and fingers, did not become significant until the wrist extended beyond neutral (Dilley et al., 2003). The explanation was that significant excursion did not occur until the resting, in-situ slack of the median nerve was taken up (Dilley et al., 2003).

2.3.3 Nerve excursion is greatest the closer to the axis of joint motion.

It is joint and body motion which changes the length of the nerve bed and therefore induces peripheral nerve excursion and eventually elongation. Neurodynamic theories suggest that the greatest amount of nerve movement will occur closest to the axis of rotation that is initiating the movement (Dilley et al., 2003; Dilley et al., 2007;

Echigo et al., 2008; Goddard & Reid, 1965; McLellan & Swash, 1976; Zoech et al., 1991). A nerve tract will not behave uniformly along its entire length as different regions along a nerve will show differing responses in excursion and strain depending on their position and relevant local anatomical relationships (Gifford, 1998; Kleinrensink, Stoeckart, Vleeming, Snijders, & Mulder, 1995; Nee, Yang, Liang, Tseng, & Coppieters, 2010; Phillips et al., 2004; Wright et al., 1996).

However, as the joint movement continues, or additional joint movements occur, there will be a continuation of nerve sliding at more distant locations along the same nerve. Nerve excursion is then progressively less compared to that which occurs at the site of the original joint movement (Nee et al., 2010; Phillips et al., 2004; Shacklock, 2005a; Topp & Boyd, 2006). For example, in cadaveric research utilising the SLR test significantly greater sciatic nerve excursion (at the level of the proximal posterior thigh) was recorded during hip flexion, when compared to more distant locations such as the spinal nerve roots at the level of the intervertebral foramen (Goddard & Reid, 1965) and the tibial nerve two centimetres above the popliteal crease (Coppieters et al., 2006).

Dilley et al. (2003) observed that longitudinal median nerve movement, from *in-vivo* ultrasound assessment in healthy participants, was significantly greater during wrist extension (0 - 40°), when movement was measured at the forearm (4.2mm) compared to in the upper arm (1.8mm). The same trend was shown for ulnar nerve excursion during wrist extension (0 - 40°) with movement at the distal forearm (2.1mm) significantly greater compared to the proximal forearm (1.1mm) again from *in-vivo* ultrasound assessment in healthy participants (Dilley et al., 2007).

2.3.4 Increased neural tension will reduce nerve excursion and joint range.

Multiple joint movements and body position significantly influence the relationship between nerve excursion and strain (Coppieters & Butler, 2008). Nerve excursion that is present with single joint movement will diminish with additional joint movements that increase tension (Coppieters & Alshami, 2007; Coppieters et al., 2006; Coppieters et al., 2009; Wright et al., 1996). Significant increases in nerve strain will occur once sliding diminishes and elongation occurs. It is during this elongation that nerve tension increases exponentially (Bay, Sharkey, & Szabo, 1997; Kwan et al., 1992; Millesi, Zoch, & Reihsner, 1995; Sunderland & Bradley, 1961a) and, potentially, a similar incraese in intraneural pressures (Bay et al., 1997; Charnley, 1951; Kwan et al., 1992; Millesi et al., 1995; Sunderland, 1990; Sunderland & Bradley, 1961a; Topp & Boyd, 2006). For example, cadaver studies have demonstrated that tibial, medial and lateral plantar (Alshami, Babri, Souvlis, & Coppieters, 2008) and median (Coppieters & Alshami, 2007; Coppieters & Butler, 2008) nerve strain significantly increased with additional joint movements that elongated the nerve bed. Tibial nerve strain significantly increased, during ankle dorsiflexion, as the proximal aspect of the nerve tract was elongated (by adding hip flexion and knee extension) (Alshami et al., 2008). The same phenomenon was witnessed in the medial and lateral plantar nerves, whereby nerve strain was significantly higher in a pre-tensioned position (ankle dorsiflexion) compared to a unloaded position (ankle plantarflexion) (Alshami et al., 2008).

In-vivo analyses show a similar relationship between nerve strain/tension and joint position. In participants undergoing total hip joint replacement, the recorded sciatic nerve strain induced with knee extension was significantly greater when the hip was positioned at 45° flexion compared to a neutral position (Fleming et al., 2003). *In-vivo* measurement of median nerve strain, measured at the proximal forearm, was

greater when the shoulder was at 90° abduction (2% strain) compared to 45° abduction (1.5% strain) (Dilley et al., 2003). Significantly less median nerve excursion at the level of the wrist, induced by wrist extension, was observed when the median nerve was pre-tensioned (elbow positioned in extension) compared to when it was unloaded (elbow positioned in flexion) (Coppieters & Alshami, 2007; Coppieters & Butler, 2008). In accordance with the decreased median nerve excursion seen in the pre-tensioned position, Coppieters and Alshami (2007) noted that there was a matching increase in the amount of nerve strain recorded.

This same relationship has also been observed in a pathological situation. For example, the presence of a lumbar intervertebral disc (IVD) herniation will potentially cause a mechanical deformation of the adjacent dural sheath. This increase in neural tension may cause a decrease in spinal ROM and also spinal nerve root excursion (Breig, 1978; Shacklock, 2007). Irrespective of symptom exacerbation, from a purely mechanistic perspective, it is this increase in relative neural strain and tension that potentially limits hip ROM during a SLR in the presence of an IVD herniation (Breig & Troup, 1979b; Charnley, 1951; Falconer et al., 1948; Goddard & Reid, 1965; O'Connell, 1946; Woodhall & Hayes, 1950).

Recent studies have examined the influence of neural mobilisation upon nerve mechanics in cadavers (Coppieters & Alshami, 2007; Coppieters & Butler, 2008) and *in-vivo* (Coppieters et al., 2009; Echigo et al., 2008). Sliding techniques have been shown to result in significantly more nerve excursion coupled with less strain compared to tensioning techniques (Coppieters & Alshami, 2007; Coppieters & Butler, 2008).

Clinically the influence of additional neural strain and tension can be seen during neurodynamic testing where joint ROM decreases as tension is progressively added to the PNS. This is a key premise of neurodynamic testing. For example, studies

which have examined knee ROM during a slump test have concluded that significantly less knee extension occurred with the addition of cervical flexion (Fidel, Martin, Dankaerts, Allison, & Hall, 1996; Herrington, Bendix, Cornwell, Fielden, & Hankey, 2008; Johnson & Chiarello, 1997; Tucker, Reid, & McNair, 2007). The explanation given for the reduction in knee extension was that cervical flexion imposed additional tension upon the neuromeningeal structures at the spinal cord and nerve roots which led to a reciprocal increase in tension further down to the sciatic nerve tract (Fidel et al., 1996; Herrington et al., 2008; Johnson & Chiarello, 1997; Tucker et al., 2007; Yeung, Jones, & Hall, 1997).

2.3.5 Convergence and tension points.

As the body moves, the tension that is imposed upon the PNS will differ depending on the proximity of the nerve to the moving joints (Phillips et al., 2004). In order to dissipate mechanical forces, peripheral nerve movement occurs along the resultant pressure gradient, towards the site of joint movement (Phillips et al., 2004; Shacklock, 1995b, 2005a; Topp & Boyd, 2006). Therefore, from each side of a joint, the nerve will slide towards that joint axis allowing more constant movement between the nerve and the mechanical interface for minimal force summation and avoidance of excessive elongation stress (Butler, 1989, 2000; Shacklock, 2005a). This phenomenon has been referred to as 'convergence' (Butler, 2000; Shacklock, 2005a; Topp & Boyd, 2006).

This pattern of nerve movement has been witnessed in many *in-vivo* studies in humans. For example, the median nerve moved toward the wrist during wrist extension (Dilley et al., 2003; Dilley et al., 2007; Echigo et al., 2008; Hough et al., 2000b; Tuzuner et al., 2004), toward the elbow during elbow extension (Coppieters et al., 2009;

Dilley et al., 2003), toward the shoulder with shoulder abduction (Dilley et al., 2003) or scapula protraction (Julius, Lees, Dilley, & Lynn, 2004) and toward the cervical spine during contralateral cervical side-flexion (Coppieters et al., 2009; Dilley et al., 2003; Julius et al., 2004). The ulnar nerve moved toward the wrist during wrist extension and towards the elbow during elbow extension (Dilley et al., 2007).

Although this movement pattern appears to be consistent for the peripheral nerve tracts of the limbs, the same cannot be said for the spinal cord and spinal nerve roots (Butler, 2000; Shacklock, 2005a). Several studies have concluded that the neuromeningeal tissues moved in opposite directions, in response to spinal movements, at varied spinal segments (Reid, 1960; Smith, 1956; Yuan, Dougherty, & Marguiles, 1998). It is believed that relative regional spinal flexibility is greatest at C5-6, T6 and L4-5 and therefore neural movement will occur relative to these points (Butler, 1989, 2000; Shacklock, 2005a). For example, the convergent movement of the spinal cord towards C6, during cervical flexion, has been seen both in cadaveric studies of monkeys (Smith, 1956) and also *in-vivo* from analysis of human neck movement using magnetic resonance imaging (MRI) (Yuan et al., 1998). The same phenomenon has been reported in the lumbar spine where lumbar nerve roots above L4/5 moved caudally and those below L4/5 moved cephalically (Louis, 1981).

Butler (1989, 2000) has referred to these spinal regions as 'tension points'. Depending on a person's individual flexibility, the locations of these regions may not be consistent across a population (Butler, 1989, 2000). However, the phenomenon of convergence will remain and, relative to both the areas of greater segmental movement and the point of initial movement, sliding and elongation of the nervous system will occur in relation to the pressure gradients created at these locations and during specific movements.

2.3.6 Regional peripheral nerve excursion.

Contemporary research to assess peripheral nerve excursion has been greatly enhanced with modern imaging techniques. For example, USI has become an increasingly popular method as it allows real-time, *in-vivo* analysis of nerve movement that is non-invasive (Dilley, Greening, Lynn, Leary, & Morris, 2001; Hough, Moore, & Jones, 2000a; Hough et al., 2000b). The following sections detail specific regional assessment of peripheral nerve movement. It is important to appreciate the amount of nerve excursion that has been seen in order to provide context for studies which examine nerve excursion in pathological groups or in response to neural mobilisation.

2.3.6.1 Upper limb nerve movement.

Longitudinal median nerve excursion *in-vivo* (Table 1) has been reported to range from 0.1 - 15.3mm (Coppieters et al., 2009; Dilley et al., 2001; Dilley et al., 2003; Echigo et al., 2008; Hough et al., 2000b; Julius et al., 2004; McLellan & Swash, 1976). Cadaveric research of longitudinal median nerve excursion has shown a range of 0 - 23.8mm (Coppieters & Alshami, 2007; Coppieters & Butler, 2008; Szabo et al., 1994; Wilgis & Murphy, 1986; Wright et al., 1996; Yoshii et al., 2008). Transverse nerve excursion of the median nerve has been reported to range from 1.5 – 3.0mm in an *in-vivo* study (Nakamichi & Tachibana, 1995) compared to 0.9 – 1.9mm in a cadaver study (Yoshii et al., 2008).

Longitudinal excursion of the ulnar nerve *in-vivo* (Table 1) has been reported to range from 0.1 - 4.0mm (Dilley et al., 2007) compared to 0 - 13.8mm reported in cadaver studies (Coppieters & Butler, 2008; Grewal et al., 2000; Wilgis & Murphy, 1986; Wright, Glowczewskie, Cowin, & Wheeler, 2001).

To date, radial nerve excursion has not been quantified *in-vivo*. However, Wright et al. (2005) analysed radial nerve excursion, in ten transthoracic cadaver arms, at both the wrist and the elbow. At the wrist, excursion ranged from 0 - 4.3mm for single joint movements and 1.8 - 7.6mm for multiple joint movements. This is compared with excursion at the elbow, which ranged from 0 - 8.8mm for single joint movements and 2.8 - 11.4mm for multiple joint movements (Wright, Glowczewskie, Cowin, & Wheeler, 2005).

Wilgis and Murphy (1986) analysed excursion of the brachial plexus in 15 intact cadaver arms. The range of movement (full flexion-extension arc at the shoulder joint) was 11-17mm, with measurement occurring directly proximal to the shoulder joint. *In-vivo* excursion of the brachial plexus has not been reported.

In summary, for the peripheral nerves of the upper limb there are limited numbers of *in-vivo* analyses, restricted to the median and ulnar nerves. An upper value of median and ulnar nerve excursion *in-vivo*, respectively, was 15.3mm and 4mm.

2.3.6.2 Lower limb nerve movement.

To date, there is a paucity of research which has quantified lower limb nerve movement *in-vivo*. *In-vivo* analysis of femoral nerve excursion (Table 1) was examined by Hsu et al. (2007) in response to different ranges of hip lateral rotation. A range of 0.99 - 2.63mm ventral and 0.68 - 1.22mm lateral excursion was seen with lateral hip rotation ranging from 0 - 45°.

Following cadaveric studies, sciatic nerve excursion has been reported to range from 3.47 − 46.8mm (Beith, Richards, & Robins, 1994; Coppieters et al., 2006;

Goddard & Reid, 1965) whilst tibial nerve excursion has been reported to range from 3.1 – 49.2mm (Beith et al., 1994; Coppieters et al., 2006).

In-vivo analysis of lumbo-sacral nerve root excursion has not been reported. Longitudinal lumbosacral nerve root excursion, in cadaveric studies, has been reported to range from 0.00 – 10mm (Breig & Troup, 1979b; Gilbert et al., 2007a, 2007b; Goddard & Reid, 1965; Inman & Saunders, 1941; Ko et al., 2006; Smith, Massie, Chesnut, & Garfin, 1993; Sunderland & Bradley, 1961b). Two studies analysed transverse (perpendicular) excursion of the lumbosacral nerve roots in cadavers and reported a range of 0.02 – 0.23mm, in response to the SLR test (Gilbert et al., 2007a, 2007b).

In summary, for the peripheral nerves of the lower limb there is less *in-vivo* analyses available, restricted to the femoral nerve only. The upper limit of *in-vivo* femoral nerve excursion has been shown to be 2.63mm.

Table 1. *In-vivo* assessment of longitudinal nerve excursion in humans.

Nerve	Assessment methods	Location of measurement			Joint movement	Limb position	References
		Upper arm	Forearm	Wrist			
Median	USI	5.9mm -	3.5mm -		Protraction of scapulothoracic joint	Shoulder 90° flexion and 20° abduction, elbow extended, forearm supination 45°, hand and fingers neutral.	(Julius et al., 2004)
	USI	10.2mm +			Simultaneous elbow extension and ipsilateral neck side-flexion	Shoulder abducted to 90° and external rotation, wrist in neutral, fingers in extension.	(Coppieters et al., 2009)
	USI		3mm -		Elbow extension from 90° flexion to neutral	Shoulder abducted to 90°, wrist in neutral	(Dilley et al., 2003)
	USI, needle electrode movement	7.4mm +	2.9mm + - 15.3mm +		Extension of wrist and fingers from neutral	Shoulder in 20-45° abduction, elbow extension, forearm 80° supination	(Dilley et al., 2001; Dilley et al., 2003; Echigo et al., 2008; Hough et al., 2000b; McLellan & Swash, 1976)
Ulnar	USI		0.8mm -		Elbow flexion from 0° to 90°	Shoulder abducted to 90°, wrist in neutral	(Dilley et al., 2007)
	USI		4.0mm +		Extension of wrist and fingers from neutral	Shoulder in 90° abduction and elbow 90° flexion	(Dilley et al., 2007)
	USI		3.0mm +		Extension of wrist and fingers from neutral	Shoulder at 40°adduction and elbow extended	(Dilley et al., 2007)

Nerve	Assessment methods	Location of measurement Inguinal crease	Joint movement	Limb position	References
Femoral	USI	0.99 - 2.63mm ventral 0.68 - 1.22mm lateral	Hip external rotation 0 - 45°	Supine lying with the hip at 15° abduction	(Hsu et al., 2007)

USI: ultrasound imaging. + = distal nerve excursion. - = proximal nerve excursion

2.4 CLINICAL IMPLICATIONS OF IMPAIRED NERVE MOVEMENT

A loss of free excursion of the PNS has been reported in peripheral neuropathies and certain clinical situations, for example non-specific arm pain (Dilley et al., 2008; Greening et al., 2005; Greening et al., 2001; Greening et al., 1999; Wilgis & Murphy, 1986), carpal tunnel syndrome (Erel et al., 2003; Hough et al., 2007a; Hunter, 1996; Nakamichi & Tachibana, 1995; Rozmaryn et al., 1998; Szabo et al., 1994), cubital tunnel syndrome (Oskay et al., 2010) and whiplash (Greening et al., 2005). However, controversy exists as to whether impaired nerve excursion exists in these clinical conditions.

For example, there is conflicting evidence in that some studies report decreased longitudinal nerve sliding in populations with various peripheral neuropathies (Erel et al., 2003; Greening et al., 2001; Greening et al., 1999; Hough et al., 2007a; Nakamichi & Tachibana, 1995; Valls-Sole, Alvarez, & Nunez, 1995). Others have found no significant differences in nerve excursion between clinical populations and controls (Dilley et al., 2008; Erel et al., 2003). Furthermore, several studies have shown a significant reduction in transverse nerve excursion in certain clinical conditions (i.e. CTS) (Erel et al., 2003; Nakamichi & Tachibana, 1995) which can be present without change to longitudinal excursion (Erel et al., 2003). This situation is compounded by the fact that comparative critical appraisal of this body of evidence is problematic in that different methods of nerve excursion assessment have been used (i.e. different imaging techniques and data analysis), different pathological populations have been studied, different joint movement have been used to induce nerve excursion and different participant positions have been used.

The sections of a peripheral nerve immediately adjacent to a region that is unable to slide freely may be placed under more elongation load and stress as the nerve

bed moves (Dilley et al., 2008; Erel et al., 2003; Greening et al., 2001; Hunter, 1991, 1996; Szabo et al., 1994). Intrinsic shear trauma to the nerve itself is also possible when a loss of sliding occurs (McLellan, 1975; Wilgis & Murphy, 1986). It is also believed that the more nerve excursion is restricted, the greater the adverse mechanical and physiological consequences, therefore a dose-dependent response is thought to be apparent (Nakamichi & Tachibana, 1995).

In regard to the therapeutic use of neural mobilisation, it is widely believed that exercises help to promote nerve excursion and in doing so must therefore have a positive effect on neural mechanics and physiology. The following sections provide background to clinical situations that may lead to impaired nerve movement.

2.4.1 Neural mechanosensitivity.

Walsh and Hall have stated that "neural tissue mechanosensitivity (local tenderness over nerve trunks and pain in response to limb movements that elongate the nerve) is a recognised feature of pain of neural origin" (Walsh & Hall, 2009b, p. 623). Mechanosensitivity refers to the generation of impulses, in response to mechanical stress (i.e. stretching, compression forces, etc), by the neural tissue (Boyd, Wanek, Gray, & Topp, 2009; Dilley et al., 2005; Shacklock, 1995b; Walsh & Hall, 2009a, 2009b). Mechanical loads that are normally innocuous may trigger the activation of nociceptive ectopic signals in sensitised neural tissue (Schmid et al., 2009; van der Heide, Bourgoin, Eils, Garnevall, & Blackmore, 2006). Mechanosensitivity is a normal physiological response which is considered a defence mechanism of the nervous system (Boyd et al., 2009).

The underlying pathological basis of increased neural mechanosensitivity remains contentious (Hall & Elvey, 2004). It is generally well accepted that the stimulation and sensitisation of the nociceptive nervi nervorum is a feature of mechanosensitivity (Bove & Light, 1997; Hall & Elvey, 2004; van der Heide et al., 2006). It is thought that the nervi nervorum are stimulated in the presence of excessive mechanical and/or chemical stimuli (Bove & Light, 1995, 1997; Fernández-de-las-Peñas et al., 2009; Hall & Elvey, 1999; Sauer et al., 1999).

From a clinical perspective, neural mechanosensitivity is determined by the response of neural tissues to elongation (which is induced by neurodynamic tests) and to nerve palpation (Boyd et al., 2009; Dilley et al., 2005; Dilley et al., 2008; Greening et al., 2005; Walsh & Hall, 2009a). Neurodynamic tests use sequences of joint motion in order to progressively and selectively move and stretch a particular nerve tract (Byl et al., 2002).

The underlying premise of neurodynamic testing is to progressively elongate the nerve bed, and therefore the nerve. As this is done, the level of neural mechanosensitivity can be judged in regard to the symptomatic response. The ulnar nerve neurodynamic test has shown to increase strain in the ulnar nerve in the region of 8.6% (Byl et al., 2002) and 8.2% for the median nerve neurodynamic test (Byl et al., 2002). Other authors suggest the median nerve may be exposed to 11% elongation during median neurodynamic testing (Topp & Boyd, 2006). In the presence of an experimentally induced local neuritis in rats, intact A and C fibres have been shown to become mechanosensitive when exposed to elongation forces in excess of 3% elongation (Dilley et al., 2005).

2.4.2 Neural oedema leading to impaired nerve movement.

Intraneural oedema is a common manifestation of nerve injury (Brown et al., 2011; Troup, 1986). Repetitive irritation of a peripheral nerve may cause stimulation of the nervi nervorum whose response is to release substance-P and calcitonin gene-related peptide (Bove & Light, 1997; Shacklock, 2005a) resulting in increased local intraneural blood flow (Zochodne & Ho, 1991).

Studies involving animals have shown dramatic increases in nerve CSA (52%), indicative of intraneural oedema, as a result of focal compression injury (Beel et al., 1984). Imaging (i.e. USI and MRI) studies have shown significant increases in median nerve CSA in people with CTS compared to matched controls, particularly at the proximal entrance to the carpal tunnel (Allmann et al., 1997; El Miedany, Aty, & Ashour, 2004; Hammer, Hovden, Haavardsholm, & Kvien, 2006; Klauser et al., 2009; Mondelli, Filippou, Aretini, Frediani, & Reale, 2008), the extent being correlated with increased symptom severity (El Miedany et al., 2004). It is believed that swelling of a nerve proximal to an entrapment site may lead to decreased nerve movement (Allmann et al., 1997; McLellan & Swash, 1976; Shacklock, 2005a; Valls-Sole et al., 1995; Wilgis & Murphy, 1986).

The mechanical forces sustained through various types of peripheral nerve injury may cause disruption of the tight epithelial bonds within the walls of the intraneural vessels. This may lead to increased permeability of the blood-nerve barrier (Brown et al., 2011; Gifford, 1998; Kobayashi et al., 2009; Olmarker, Rydevik, & Holm, 1989; Rempel & Diao, 2004; Totten & Hunter, 1991) and the perineurial diffusion barrier (Keir & Rempel, 2005; Mackinnon, 2002; Rydevik & Lundborg, 1977; Sunderland, 1978). Failure at these barriers can cause extravasation of fluid and

proteins resulting in intraneural oedema which may eventually lead to intraneural fibrosis and impaired nerve function (Lundborg & Rydevik, 1973).

It is difficult for a peripheral nerve to cope with intraneural oedema as there is no lymphatic drainage present within the endoneurial and perineurial spaces (George & Smith, 1996; Keir & Rempel, 2005; Lundborg, 1975; Lundborg, Myers, & Powell, 1983; Oskay et al., 2010; Rempel & Diao, 2004; Rydevik et al., 1981). An intact blood-nerve barrier also limits the dispersion of endoneurial fluid (Lundborg, 1975; Lundborg et al., 1983; Mackinnon, 2002; Rydevik et al., 1981; Sunderland, 1978) which means there is no capacity for drainage of oedema within the perineurium and endoneurium. This can lead to what has been referred to as a "compartment syndrome in miniature" (Lundborg et al., 1983; Mackinnon, 2002). Subsequently it can take a long time for intraneural oedema to dissipate. In the rat sciatic nerve, intraneural oedema was still present up to 28 days following external compression of 30mmHg applied for two hours (Powell & Myers, 1986).

2.4.3 Neural fibrosis leading to impaired nerve movement.

Neural fibrosis can impair nerve sliding (Erel et al., 2010; Hunter, 1991, 1996; Kobayashi, Shizu, Suzuki, Asai, & Yoshizawa, 2003; LaBan, Friedman, & Zemenick, 1986; Wilgis & Murphy, 1986) which may lead to mechanosensitivity due to inappropriate dissipation of tensile forces (Beith et al., 1994; Breig & Marions, 1963; Butler, 2000; Dilley et al., 2001; Dilley et al., 2003; Erel et al., 2003; Goddard & Reid, 1965; Kobayashi et al., 2010; Walsh, 2005).

An *in-vivo* study, by Boyd et al. (2005), involved rats that were exposed to a compression injury. They exhibited significantly decreased sciatic nerve excursion and

increased nerve strain from seven days post-injury, compared to a sham injury group. These authors suggested that changes in the mechanical properties of the injured nerve, through alteration in endoneurial collagen organisation, lead to increased stiffness of the nerve resulting in increased strain and decreased excursion when exposed to movement (Boyd et al., 2005). However, nerve strain levels of the injured rats returned to a similar level to the sham group at 21 days post-injury. The authors suggest that this shows modification of the mechanical behaviour of the injured neural tissue over this period of time (Boyd et al., 2005).

Extraneural fibrosis of the mesoneurium and epineurium can occur resulting in internal scarring and adhesion of the nerve to adjacent tissues (Abe et al., 2005; Bove & Light, 1997; Hunter, 1991, 1996; Mackinnon, 2002; Oskay et al., 2010; Rozmaryn et al., 1998; Walsh, 2005). Intraneural fibrosis can result in the loss of internal fascicular sliding and the loss of the undulations evident in the internal connective tissue layers (Oskay et al., 2010; Sunderland, 1965; Walsh, 2005).

Both extraneural and intraneural fibrosis has been seen in studies involving animals which have been exposed to highly repetitive reaching and grasping tasks. Neural fibrosis following this type of mechanical stress is believed to occur in people with idiopathic CTS which is linked to high-repetition work and vibrational forces (Clark, Al-Shatti, Barr, Amin, & Barbe, 2004; Clark et al., 2003).

The presence of mast cells, granular tissue, fibroblasts and disorganised collagen fibres have been observed, histologically, in the examination of extraneural fibrotic scar tissue with adherent lumbosacral nerve roots (Kobayashi et al., 2010) and idiopathic CTS (Clark et al., 2004; Clark et al., 2003; Ettema, Amadio, Zhao, Wold, & An, 2004). It is speculated that tethering of peripheral nerves may have a negative impact on intraneural microcirculation and perfusion (Burke, Ellis, McKenna, & Bradley, 2003;

Hunter, 1991, 1996) and in turn may lead to intraneural fibrosis (Abe et al., 2005; Lundborg & Dahlin, 1996; Rozmaryn et al., 1998).

Two studies have shown that surgical removal of extraneural adhesions from lumbosacral nerve roots, in the presence of IVD herniation, have resulted in significant increases in nerve root excursion during a reverse-SLR (Kobayashi et al., 2003; Kobayashi et al., 2010). These same studies have also shown that nerve root adhesions can reduce both intraradicular blood flow (Kobayashi et al., 2003) and also radicular action potential amplitude (Kobayashi et al., 2010). However, there is some contention to the influence that extraneural fibrosis may have in regard to research which concluded that there was no strong correlation evident between the size and shape of intervertebral disc bulges, as seen on MRI, and limitation in hip ROM during SLR (Thelander, Fagerlund, Fribery, & Larsson, 1992).

The ability of the PNS to slide against its mechanical interface is believed to make the PNS vulnerable to friction, strain and fibrosis (Hunter, 1991, 1996; Keir & Rempel, 2005; Mackinnon, 2002; McLellan, 1975; Wright et al., 2001). For example, following experimentally induced peripheral nerve adhesion in rabbits, Abe et al. (2005) observed marked increases in nerve strain during limb movement that was proportional to the degree of neural fibrosis present.

Neural fibrosis has also been linked to neural compression. The potential for decreased nerve excursion, in the presence of neural fibrosis, may in turn lead to greater tractional forces, during limb movement, resulting in nerve compression (Abe et al., 2005; Brown et al., 2011; Hunter, 1991, 1996; Wright et al., 2001) and nociceptive stimulation resulting in neurogenic symptoms (Butler, 2000; Clark et al., 2003; Dilley et al., 2005; Walsh, 2005). This could lead to uneven tension distribution, for example at points close to the site of decreased nerve sliding (Breig & Marions, 1963; Dilley et al.,

2008; Hunter, 1991, 1996). It is possible that the scar tissue itself may eventually become innervated and therefore be a primary source of neurogenic pain (Bove & Light, 1997).

In summary, the presence of intraneural fibrosis leading to impaired nerve excursion may increase both elongation and compressive forces at and near the site of nerve injury. This series of events has the capacity to evolve into a self-perpetuating vicious circle of pathophysiological events which ultimately impair the biomechanical and physiological capacity of the nerve (Bove & Light, 1997)

2.5 NEURAL MOBILISATION

The concept of *adverse neural tension* was introduced by Breig (1978). On the basis of adverse neural tension, further discussion regarding the use of techniques to improve neural mobility evolved (Breig, 1978). In this regard, adverse neural tension implied compromise of the normal compliance within neural tissues which detracted from the ability to cope with strain (Hall et al., 1998). As a consequence, the early premise of focused therapeutic intervention upon the nervous system often involved stretching in order to combat perceived neural tension (Shacklock, 2005b). Some of the initial neural mobilisation techniques were aggressive, involving end-range stretching of the neural tissues which were often sustained (Fahrni, 1966; Kornberg & Lew, 1989; Marshall, 1883; Shacklock, 1995a, 2005a).

There has been a shift away from describing neural mobilisation simply in mechanical terms. Some were uncomfortable with the use of the phrase 'adverse neural tension', as the strategy for dealing with tension, from a therapist's perspective, is to

stretch (Hall et al., 1998; Shacklock, 2005a). This is a strategy that delicate and sensitised neural tissue will not always tolerate well (Shacklock, 2005a).

Essentially, neural mobilisation techniques have been developed from neurodynamic tests (Bertolini et al., 2009; Butler & Gifford, 1989b; Byl et al., 2002; Coppieters et al., 2009; Maitland, 1985; Shacklock, 1995b). As neurobiology and biomechanical knowledge has developed and progressed, along with a better appreciation and acceptance of neurodynamics, neural mobilisation has evolved with the introduction of more contemporary mobilisations, such as "sliding techniques" or "tensioning techniques" (Coppieters & Alshami, 2007; Coppieters & Butler, 2008; Coppieters et al., 2009; Echigo et al., 2008).

"In not considering mechanical treatment of the neuraxis in physiotherapy, treatment of the target tissues alone may in some cases lead to ineffective and temporary results" (Shacklock et al., 1994, p. 33). Treatment of neurodynamic dysfunction can be overlooked or ignored by clinicians who lack knowledge regarding peripheral nerve biomechanics and physiology. However it is vital that neurodynamic function is not ignored in order to allow full recovery of many common musculoskeletal pathologies (Butler et al., 1994). Mobilisation of the nervous system is now considered an important adjunct in the treatment of musculoskeletal disorders (Herrington, 2006). Neural mobilisation techniques provide a means of direct therapeutic application to the nervous system (Shacklock, 1995a, 2005a).

The principle aim of neural mobilisation is to restore the dynamic balance between the relative movement of neural tissues to their surrounding mechanical interfaces, thereby reducing extrinsic pressures on the neural tissue and promotion of optimum neurophysiologic function (Bertolini et al., 2009; Brown et al., 2011; Butler,

2000; Butler et al., 1994; Gifford, 1998; Herrington, 2006; Kitteringham, 1996; Shacklock, 1995b, 2005a).

2.5.1 The influence of neural mobilisation upon impaired nerve excursion.

"The ultimate aim of treatment is to restore the patients' range of nervous system movement and stretch capabilities to normalise the sensitivity of the system" (Butler et al., 1994, p. 693). It remains unclear as to whether neural mobilisation has a treatment effect from influence of nerve mechanics, nerve physiology or other mechanisms (Beneciuk et al., 2009; Brown et al., 2011), or whether in fact it is a combination of these. It is easy to view neural mobilisation and neurodynamics purely from a mechanistic perspective. This is inappropriate as the concept of neurodynamics involves an intimate relationship between physical neural mechanics and consequent physiological responses.

2.5.1.1 Mechanical influences of neural mobilisation on nerve excursion.

A loss of nerve mobility is believed to be a potential aetiological factor of many peripheral neuropathies. Many authors have speculated that one of the primary benefits of neural mobilisation is to promote nerve excursion in order to breakdown neural fibrosis and tethering and restore optimal nerve mobility (Akalin et al., 2002; Bialosky et al., 2009b; Brown et al., 2011; Coppieters & Alshami, 2007; Fahrni, 1966; George, 2002; González-Iglesias et al., 2010; Kitteringham, 1996; Medina McKeon & Yancosek, 2008; Oskay et al., 2010; Pinar et al., 2005; Rozmaryn et al., 1998; Szabo et al., 1994). The prophylactic use of exercises to promote nerve excursion following surgery (i.e. carpal tunnel release surgery), to mitigate the potential for extraneural

fibrosis, has been advocated (Coppieters & Alshami, 2007; Fahrni, 1966; Hunter, 1991, 1996; Totten & Hunter, 1991), but also challenged (Scrimshaw & Maher, 2001).

The fundamental problem with this proposition is that there is very little evidence to support the claim that neural mobilisation will improve nerve mobility in the presence of impaired nerve excursion, for example following neural fibrosis and adhesions. Furthermore, there is limited evidence (and that is controversial) to suggest that loss of nerve mobility is in fact a factor in peripheral nerve disorders (see 2.4).

Theories suggest that neural mobilisation may also optimise the viscoelastic properties of neural tissue and increase its extensibility (Beneciuk et al., 2009; Fidel et al., 1996; Méndez-Sánchez et al., 2010; Shacklock, 1995b, 2005a; Talebi, Taghipour-Darzi, & Norouzi-Fashkhami, 2010). It has been argued that an increase in the elongation capacity and extensibility of neural tissue could potentially decrease the amount of stress imposed during movement (Beneciuk et al., 2009; Fidel et al., 1996; Herrington, 2006; Méndez-Sánchez et al., 2010). An *in-vivo* study by Fidel et al. (1996), which examined changes in knee ROM following repeated passive knee extension movements, consistent with several neural mobilisation exercises, resulted in significantly increased knee extension (towards terminal knee extension) at both first onset of symptoms and maximum tolerable symptoms during a slump test.

Similar findings were seen with an *in-vivo* study in asymptomatic participants which compared a group receiving neural mobilisation (tensioners) compared to a sham neural mobilisation group. Significant increases of elbow extension and significant decreases in sensory descriptors, during a median nerve neurodynamic test, were seen in the neural mobilisation group compared to the sham group, which were seen both immediately and at one-week follow-up (Beneciuk et al., 2009). It has been suggested

that improvements in joint ROM may, in part, have some basis in improved nerve compliance and elongation (Beneciuk et al., 2009; Fidel et al., 1996).

2.5.1.2 Physiological influences of neural mobilisation on nerve excursion.

Theories suggest that enhancing the sliding action of peripheral nerves against their mechanical interface may in turn promote a mechanical 'milking effect' upon the nerve (Akalin et al., 2002; Bardak et al., 2009; Baysal et al., 2006; Coppieters et al., 2004; Coppieters & Butler, 2008; Rozmaryn et al., 1998; Seradge, Parker, Baer, Mayfield, & Schall, 2002; Shacklock, 2005a). It is believed that this action has the potential to exploit the thixotropic properties that peripheral nerves possess which may assist axoplasmic flow (Baysal et al., 2006; Butler, 1989; Coppieters et al., 2004; Coppieters & Butler, 2008; Dahlin & McLean, 1986; Heebner & Roddey, 2008; Ogata & Naito, 1986; Oskay et al., 2010; Tal-Akabi & Rushton, 2000; Talebi et al., 2010; Wall et al., 1992), intraneural circulation, removal of metabolic wastes and removal of oedema (Akalin et al., 2002; Bardak et al., 2009; Baysal et al., 2006; Bialosky et al., 2009b; Burke et al., 2003; Coppieters et al., 2004; Coppieters & Butler, 2008; Coppieters, Stappaerts, Wouters, & Janssens, 2003b; Medina McKeon & Yancosek, 2008; Oskay et al., 2010; Rozmaryn et al., 1998; Talebi et al., 2010). As intraneural oedema is believed to contribute to impaired nerve excursion (Allmann et al., 1997; McLellan & Swash, 1976; Shacklock, 2005a; Valls-Sole et al., 1995; Wilgis & Murphy, 1986), improvement of these neurophysiological features may occur with neural mobilisation thereby enhancing nerve excursion.

Brown et al. (2011) speculated that there may also be intraneural mechanical effects which contribute to fluid dissipation. From cadaveric research, these authors proposed that a mechanical pumping effect, generated by movement at the ankle joint,

of cyclical fascicular elongation and relaxation caused greater dispersion of injected dye into the tibial nerve compared to a control limb without movement (Brown et al., 2011). It is important therefore to appreciate that the likely physiological effects of neural mobilisation occur through a combination of both intraneural and extraneural effects (Brown et al., 2011).

2.5.1.3 Analgesic influences of neural mobilisation on nerve excursion.

There is a growing body of evidence, both in human and animal research, which indicates that manual and manipulative therapy, including neural mobilisation techniques have immediate endogenous hypoalgesic and sympathoexcitatory influences (Beneciuk et al., 2009; Bialosky et al., 2009b; Cowell & Phillips, 2002; Paungmali, Vicenzino, & Smith, 2003; Sterling et al., 2010; Wright, 1995; Wright & Vicenzino, 1995; Zusman, 2004). Theoretically, neural mobilisation may improve nerve movement via an analgesic effect if mechanosensitivity is reduced. However, there is no direct evidence to support this theory.

Vicenzino et al. (1996) conducted a RCT which examined the use of a cervical lateral glide technique (which involves mobilisation of the cervical nerve roots) for the treatment of people with lateral epicondyalgia. Their hypothesis was that for this population, a manual therapy technique chosen deliberately to influence a body region distant to the site of pain would show an immediate hypoalgesic response greater than placebo or control groups. All participants had baseline impairments of a median nerve neurodynamic test and therefore a neurodynamic component to their condition. The use of the cervical lateral glide technique resulted in significant improvements in neurodynamic testing (improvement in joint ROM), pain free grip strength and pain-pressure thresholds in the treatment group over both the placebo and control groups.

The authors believed that the significant improvements of the measures of mechanosensitivity achieved from using a non-noxious manual technique (involving mobilisation of the local neural tissues), distant to the site of complaint, was due to influence of centrally mediated descending inhibitory pathways (Vicenzino, Collins, & Wright, 1996).

Sterling et al. (2010) conducted an RCT to assess the immediate effect of a cervical lateral glide technique versus manual contact in a cohort of people with chronic whiplash associated disorders. The outcome measures assessed included those associated with measurement of central hyperexcitability, for example pain pressure threshold, thermal pain thresholds and nociceptive flexion reflex. They concluded significant reductions in nociceptive flexion reflex but not of the other two measures. The authors believed that this shows further evidence of the neuromodulatory effects of spinal manual therapy, in this case consistant with a neural mobilisation.

2.5.2 Neural mobilisation techniques.

2.5.2.1 'Sliders'.

Upon initial limb movement, the inherent slack of a peripheral nerve will be taken up which then allows nerve sliding (either transverse or longitudinal) to occur (Charnley, 1951; Dilley et al., 2003; Fahrni, 1966; Shacklock, 2005a). It is possible to exploit this phenomenon when selecting neural mobilisation techniques. For example, if a sliding problem is suspected, a 'sliding' technique applied with larger amplitude within the inner to mid range of its movement is most likely to exploit nerve sliding (Coppieters & Butler, 2008; Coppieters et al., 2009; Shacklock, 2005a).

A neurodynamic slider or sliding technique is a "…manoeuvre whose purpose is to produce a sliding movement of neural structures relative to their adjacent tissue" (Shacklock, 2005a, p. 22). Sliders provide a means of physically influencing the excursion of a nerve, sliding along its nerve bed, without placing great tension upon it (Coppieters & Alshami, 2007; Coppieters & Butler, 2008; Coppieters et al., 2009; Herrington, 2006; Oskay et al., 2010; Shacklock, 2005a).

Sliders provide a combination of movements that elongate the nerve bed at one end whilst simultaneously releasing tension from the other end (Beneciuk et al., 2009; Butler, 2000; Coppieters & Alshami, 2007; Coppieters et al., 2004; Coppieters & Butler, 2008; Coppieters et al., 2009; Fernández-de-las-Peñas et al., 2010; González-Iglesias et al., 2010; Herrington, 2006; Shacklock, 2005a). This combination of movements allows the nerve to slide along its tension gradient towards the end of the tract to which tension is applied (Butler, 2000; Shacklock, 2005a). When this occurs, nerve excursion is promoted without the proportional increase in nerve tension that is associated with elongation or tensioning manoeuvres (Coppieters & Alshami, 2007; Coppieters et al., 2004; Coppieters & Butler, 2008). It is believed that sliders may also have an internal effect in promoting interfascicular and inter-fibre sliding (Oskay et al., 2010).

Sliders have been further categorised as either being one-ended or two-ended (Herrington, 2006; Shacklock, 2005a). A one-ended slider exploits nerve excursion by utilising a joint movement at one end of the nerve tract through large, early-mid range movements prior to when nerve elongation may occur (Shacklock, 2005a). An example of a one-ended slider for the sciatic nerve and lumbo-sacral nerve roots would be to use knee extension in sitting (from mid-range flexion towards extension), with the cervical spine held in neutral or extension (Figure 3).

Two-ended sliders utilise combinations of joint movements by increasing elongation at one end of the nerve bed whilst simultaneously releasing tension from a distant aspect of the nerve bed (Herrington, 2006; Shacklock, 2005a). An example of a two-ended slider for the sciatic nerve and lumbo-sacral nerve roots would be to utilise simultaneous knee extension and cervical extension in sitting (Figure 3). Depending on the combination of joint movements used, and exploiting the phenomenon of convergence, sliders can be designed to encourage either proximal or distal peripheral nerve excursion (Herrington, 2006; Shacklock, 2005a).

A. Two-ended slider   **B.** One-ended slider   **C.** Tensioner
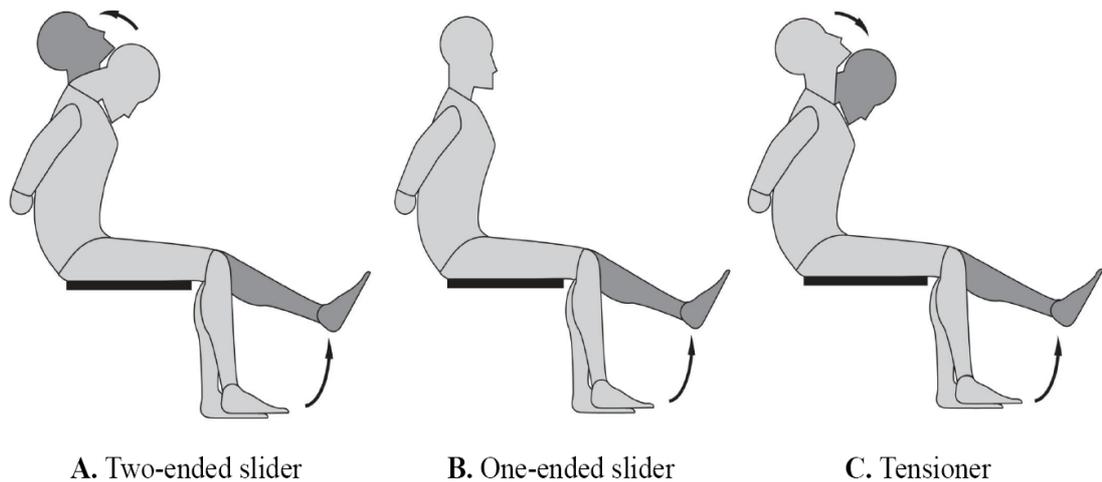
Figure 3. Sliders and Tensioners

2.5.2.2 'Tensioners'.

A tensioner or tensioning technique applied with short or large amplitude movement, within the mid–outer range is more likely to exploit nerve elongation and tension (Coppieters & Butler, 2008; Coppieters et al., 2009; Shacklock, 2005a; Talebi et al., 2010). A tensioner will utilise combinations of joint movements that will alternate between elongating the nerve bed then releasing (Beneciuk et al., 2009; Coppieters et

al., 2004; Coppieters & Butler, 2008; Coppieters et al., 2009; González-Iglesias et al., 2010; Herrington, 2006).

Tensioners exploit the viscoelastic properties of the nervous system via elongation through the length of the nerve tract (Herrington, 2006). Further to this, tensioners have been shown to also create relative excursion of the peripheral nerve (Coppieters & Butler, 2008; Coppieters et al., 2009) along with increased nerve strain (Coppieters & Butler, 2008).

It is recommended that tensioners do not extend beyond the elastic limit of the nerve and are not sustained for long periods (but rather oscillatory), as this may jeopardise and damage the integrity of the nerve (Butler, 2000; Shacklock, 2005a; Talebi et al., 2010). An example of a tensioner (Figure 3), targeted for the lumbo-sacral nerve roots and sciatic nerve tract, is moving from a sitting position with the spine in extension, hips and knees flexed and ankles plantarflexed (PF) into a slump-sitting position, where cervical and trunk flexion is combined with knee extension and ankle dorsiflexion (DF) (Herrington, 2006; Maitland, 1985).

2.5.2.3 'Sliders' versus 'tensioners'.

Cadaver (Coppieters & Butler, 2008) and *in-vivo* (Coppieters et al., 2009) research has shown that the degree of nerve excursion is greatest with a slider compared to a tensioner. Furthermore, cadaver research has shown that the amount of nerve tension created is greater with tensioners compared to sliders (Coppieters & Butler, 2008). As sliders generate significantly more nerve excursion compared to tensioners (Coppieters & Butler, 2008; Coppieters et al., 2009), sliders have been suggested to be beneficial to increase neural excursion and also for reducing pain (Shacklock, 2005a). As previously mentioned, neural mobilisation may have endogenous hypoalgesic effects

(Beneciuk et al., 2009; Bialosky et al., 2009b; Cowell & Phillips, 2002; Paungmali et al., 2003; Wright, 1995; Wright & Vicenzino, 1995; Zusman, 2004).

It follows that for patients that have significant symptoms (i.e. have increased mechanosensitivity) it is more judicious to use a sliding technique rather than a tensioning technique (Herrington, 2006; Talebi et al., 2010; Walsh, 2005). Tensioners are potentially more provocative compared to sliders due to the greater increase in neural tension (Coppieters & Alshami, 2007; Coppieters & Butler, 2008).

Theories have suggested that tensioners may be used for the enhancement of the viscoelastic function of a nerve in response to tension loads (Shacklock, 2005a; Talebi et al., 2010), however there is no empirical evidence to support this. There is also a potential for compromise of intraneural blood flow when a peripheral nerve is exposed to tension, elongation or compression (Herrington, 2006; Ogata & Naito, 1986; Shacklock, 2005a; Talebi et al., 2010). As they generate less tension within a nerve compared to tensioners, sliders may potentially lead to less compromise of intraneural blood flow (Herrington, 2006). Therefore there may be potential benefits in using sliders instead of tensioners, with potentially less risk from neural tissue hypoxia and avoidance of neural vascular compromise (Hall & Elvey, 1999; Herrington, 2006).

2.5.2.4 Neural mobilisation prescription.

As is the case with many therapeutic interventions used by physiotherapists, the prescription and dosage is rarely defined and agreed (Bialosky, Bishop, Price, Robinson, & George, 2009a; Walsh, 2005). This is no different for neural mobilisation (Walsh, 2005). Many clinical decisions need to be taken into context when prescribing exercises or deciding on dosage for any given technique.

A clinical reasoning model perpetually challenges these decisions and constantly asks questions with regard to prescription and dosage. The position is no different when considering neurodynamics and neural mobilisation. Shacklock (2008, personal communication) has reiterated this point, stating that decisions regarding the dosage and exercise prescription of neural mobilisation has not been specifically identified and must be made upon sound clinical reasoning (Shacklock, 2008).

A clinical trial conducted by Scrimshaw and Maher (2001) examined the use of neural mobilisation in the post-operative care of 81 patients undergoing lumbar spinal surgery (including discectomy, laminectomy and fusion) and compared this to standard care. These authors concluded that neural mobilisation was no more effective compared to the standard care package, both immediately post-operative and up to twelve months follow-up. Interestingly one of the discussion points was that the prescription of neural mobilisation exercises may have not been optimal. These authors highlight the lack of consensus regarding prescription of neural mobilisation, as having sought colleague opinion upon conclusion of their study, "…some colleagues are firmly of the opinion that the protocol failed because it was too vigorous, whereas a similar number are convinced that the protocol was too gentle" (Scrimshaw & Maher, 2001, p. 2650).

It is judicious initially to prescribe neural mobilisation exercises to utilise ranges of movement which do not exacerbate symptoms in order to mitigate a potential increase in mechanosensitivity (Butler, 1989; Butler & Gifford, 1989a; Koury & Scarpelli, 1994; Shacklock, 2005a; Totten & Hunter, 1991; Walsh, 2005). It would also be preferable, in acute situations, to prescribe neural mobilisation exercises that mechanically influence a region along the nerve tract distant to the hypothesised dysfunctional region (Butler, 1989; Butler & Gifford, 1989a; Kostopoulos, 2004; Shacklock, 2005a; Walsh, 2005).

As mechanosensitivity subsides, then neural mobilisation exercises can incorporate challenges to tension and also can be moved closer to the suspected location of nerve dysfunction (Butler & Gifford, 1989a; Kostopoulos, 2004; Koury & Scarpelli, 1994; Shacklock, 2005a; Talebi et al., 2010; Walsh, 2005), for example progressing from a slider to a tensioner (Herrington, 2006; Talebi et al., 2010) or specifically targeting certain limb positions and postures which may directly influence neural tension and excursion.

2.6 ULTRASOUND IMAGING OF PERIPHERAL NERVE MOVEMENT

2.6.1 Principles and properties of ultrasound imaging.

USI is an extremely versatile and cost effective method of imaging (Chiou, Chou, Chiou, Liu, & Chang, 2003; Gibbon, 1998; Hashimoto, Kramer, & Wiitala, 1999; Heinemeyer & Reimers, 1999; Martinoli, Bianchi, & Derchi, 2000; Walker, Cartwright, Wiesler, & Caress, 2004). It offers distinct advantages over other imaging methods in the ability to measure both in real-time and *in-vivo* (Chiou et al., 2003; Echigo et al., 2008; Hashimoto et al., 1999; Jeffery, 2003; Martinoli et al., 2000). Other advantages that USI has over other imaging techniques are that it is portable, non-invasive and eliminates recipient claustrophobia (Chiou et al., 2003; Hashimoto et al., 1999; Martinoli et al., 2000; Walker et al., 2004).

An important feature of USI, which must be taken into account, is that it is operator dependent (Beekman & Visser, 2003, 2004; Chiou et al., 2003; Martinoli et al., 2000; Peer, Kovacs, Harpf, & Bodner, 2002). Potentially the validity of analysis and accuracy of diagnosis is directly influenced by the skill of the operator, not only of their

technical skill in the application of the ultrasound but also of their knowledge of what is being seen (i.e. anatomy and pathology) (Peer et al., 2002).

2.6.1.1 The physics of ultrasound imaging.

USI utilises energy signals created when a sound wave is transmitted and then echoed back from a source (Jeffery, 2003). As the sound wave passes into and through the target tissues, the wave is scattered, reflected and attenuated by these tissues in a specific manner depending on the physical properties of the tissues (Bushong, 1999; Jeffery, 2003). The amount of that sound wave that is reflected back (and therefore the amount that propagates further through the tissues) is determined by the difference in acoustic impedance of the various tissues (Kossoff, 2000). Acoustic impedance is defined by the product of the tissue density multiplied by the velocity of sound wave propagation through the tissue (Bushong, 1999; Kossoff, 2000).

Analysis can be made of the speed and intensity of the reflected signals (Jeffery, 2003). For example, the acoustic impedance of air is much less than soft tissues (i.e. muscle) which in turn is much less than bone. Therefore virtually none of the sound wave will be reflected back to the transducer when the signal passes through air. This lack of reflection will be presented as a low-intensity grey-scale image, which appears visually dull/black (otherwise known as hypoechoic).

Conversely, bone has much greater acoustic impedance and will reflect back a greater proportion of the sound wave. Therefore a much brighter, high-intensity grey-scale image is created, which will appear visually to be bright/white (otherwise known as hyperechoic) (Kossoff, 2000).

2.6.1.2 Ultrasound imaging techniques.

There are several varieties of USI mode, including A-mode, B-mode, M-mode and Doppler (Anderson & McDicken, 1999; Hashimoto et al., 1999; Jeffery, 2003; Kossoff, 2000). B-mode ultrasound is the most widely used for medical imaging (Anderson & McDicken, 1999; Harvey, Pilcher, Eckersley, Blomley, & Cosgrove, 2002a; Kossoff, 2000). B-mode, or 'brightness' mode, allows grey-scale imaging whereby the image is represented by various shades of grey depending on the amplitude, and therefore brightness displayed, of the echoed signals' amplitude (Jeffery, 2003). B-mode grey-scale imaging allows real-time imaging, whereby a series of images are rapidly displayed in sequence (in the range of 25-120 frames per second) (Anderson & McDicken, 1999) allowing depiction of tissue motion (Anderson & McDicken, 1999; Harvey et al., 2002a; Jeffery, 2003; Kossoff, 2000). A great benefit of USI is that ultrasound travels very quickly through human tissues (on average 1540 metres/second) (Anderson & McDicken, 1999; Beekman & Visser, 2004; Bushong, 1999; Jeffery, 2003) therefore allowing echo creation, imaging and virtually instantaneous analysis (Anderson & McDicken, 1999).

Doppler imaging analyses the shift in frequency of reflected signals. As discussed earlier, different tissues will absorb and reflect more or less of the ultrasound beam and also at different speeds. Doppler scanning will analyse the differences in returning frequencies between the target tissues and will produce an image accordingly (Bushong, 1999; Kossoff, 2000). This frequency shift is not only created by the relative differences in the tissues physical properties, but is also relative to the speed with which it is moving (Hough et al., 2000a; Jeffery, 2003; Kossoff, 2000).

The measurement of the frequency shift is the key principle in differentiating Doppler imaging from B-mode imaging. Essentially in Doppler imaging the ultrasound

beam remains stationary and detects changes in velocity and amplitude of reflected images as the tissues underneath move. However, B-mode generally detects changes in amplitude of reflected signals as the ultrasound beam moves relative to static tissues underneath (Kossoff, 2000). Doppler imaging is most commonly used in the measurement of blood flow (Anderson & McDicken, 1999; Hough et al., 2000a).

2.6.2 Ultrasound imaging of peripheral nerves.

USI of peripheral nerves is widely reported in use both for clinical diagnostic purposes (i.e. to identify nerve compression, trauma, pathology, etc.) (Beekman, van der Plas, Uitdehaag, Schellens, & Visser, 2004; Beekman & Visser, 2003; Esselinckx et al., 1986; Fornage, 1993; Graif, Seton, Nerubai, Horoszowski, & Itzchak, 1991; Heinemeyer & Reimers, 1999) and also in the assessment of neural biomechanics (Coppieters et al., 2009; Dilley et al., 2001; Dilley et al., 2003; Dilley et al., 2007; Erel et al., 2003; Erel et al., 2010; Greening et al., 2005; Greening et al., 2001; Greening et al., 1999; Hough et al., 2000a, 2000b).

Peripheral nerves are well visualised with USI (Figure 4), but more easily within the upper limb compared to the lower limb (Beekman & Visser, 2004). Therefore it is likely this has contributed to the majority of published papers regarding USI have examined upper limb nerves. Peripheral nerves appear as hypoechoic tubes when viewed longitudinally and hypoechoic round/oval sections when viewed transversely (Beekman & Visser, 2004; Chiou et al., 2003; Fornage, 1988, 1993; Graif et al., 1991; Hashimoto et al., 1999; Hough et al., 2000a; Wilkinson, Grimmer, & Massy-Westropp, 2001).
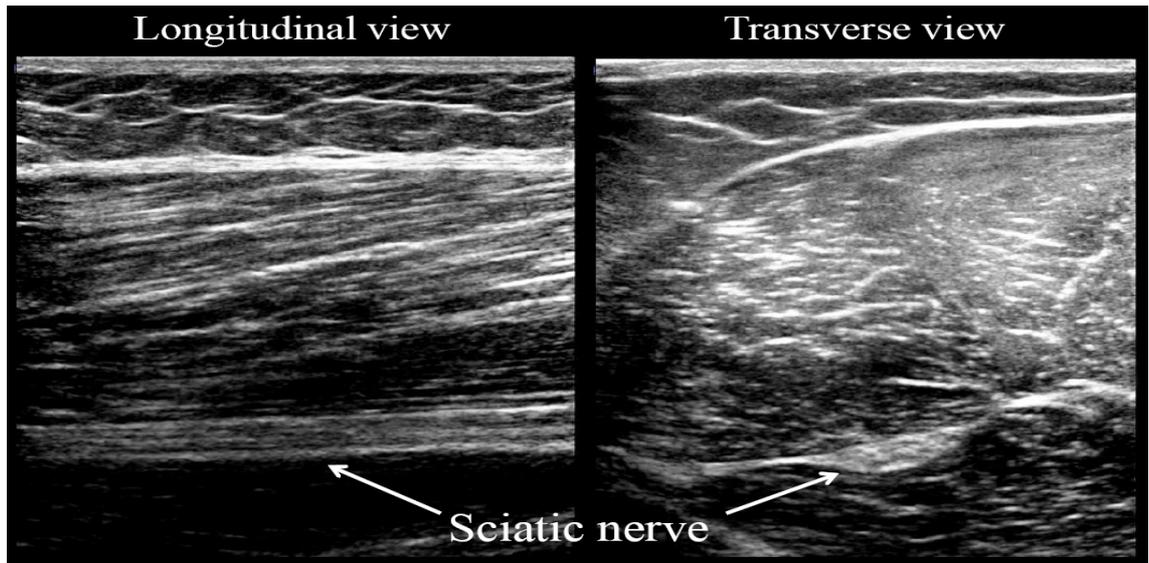
Figure 4. Ultrasound appearance of the sciatic nerve.
These images were taken at the level of the posterior mid-thigh and were collected as part of this doctoral research.

On closer inspection of longitudinal ultrasound images (Figure 5), peripheral nerves can be distinguished from neighbouring soft tissues as several hypoechoic lines (nerve fascicles) which are contained within two bolder echogenic, hyperechoic lines (epineurium) (Beekman & Visser, 2004; Chiou et al., 2003; Fornage, 1988, 1993; Graif et al., 1991; Hough et al., 2000a; Martinoli et al., 2002; Martinoli et al., 2000; Peer et al., 2002). Transverse ultrasound images (Figure 5) of peripheral nerves have a *honey-comb* appearance, as the nerve fascicles appear hypoechoic in contrast to the more hyperechoic epineurium which surrounds the fascicles (Beekman & Visser, 2004; Chiou et al., 2003; Fornage, 1993; Martinoli et al., 2000; Peer et al., 2002; Wilkinson et al., 2001).
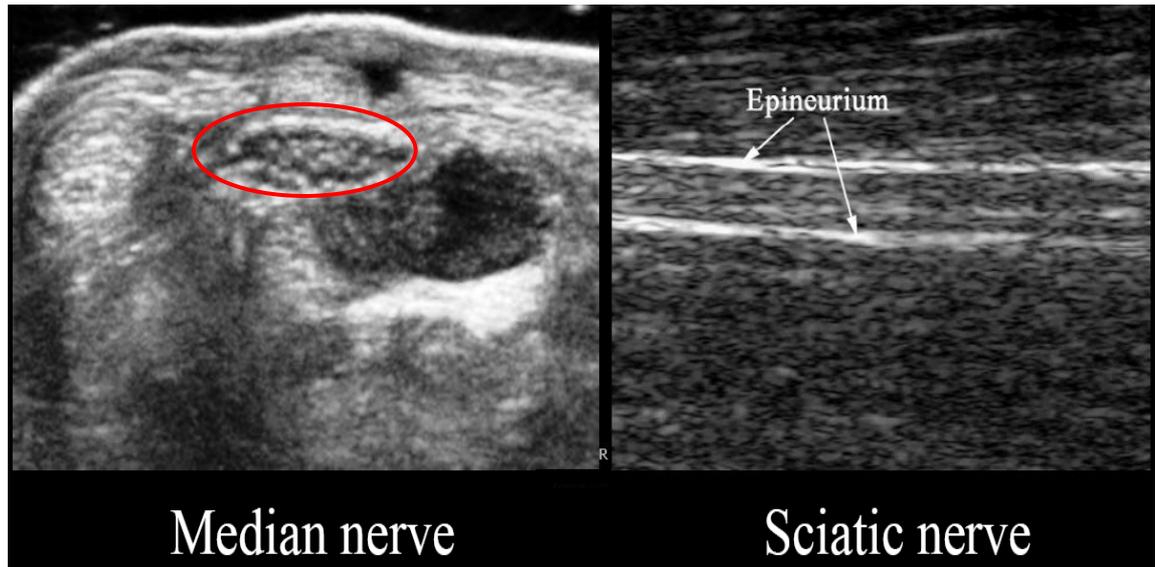
Figure 5. Detailed ultrasound appearance of peripheral nerves.
These images were taken at the level of the carpal tunnel (median nerve) and posterior mid-thigh (sciatic nerve) and were collected as part of this doctoral research.

The parallel internal echoes (fascicles), seen in peripheral nerves with longitudinal USI, present a similar appearance to that of tendon. However, nerves can be differentiated from tendon both from their anatomical location and upon initial active or passive contraction of a muscle causing relative movement of tendon and not nerve (Fornage, 1988, 1993; Hashimoto et al., 1999; Heinemeyer & Reimers, 1999) or vice versa (Heinemeyer & Reimers, 1999; Schafhalter-Zoppoth, Younger, Collins, & Gray, 2004). Tendons are also more prone to anisotropy, which describes an alteration in grey-scale patterns when altering the angle of the ultrasound beam (Hough et al., 2000a).

2.6.2.1 Ultrasound imaging of the sciatic nerve.

It is more difficult to image the lower limb nerves using USI compared to the nerves of the upper limb as the former are generally deeper and closely surrounded by other soft tissues (Beekman & Visser, 2004; Hoddick, Callen, Filly, Mahony, &

Edwards, 1984). Through most of the course of the sciatic nerve there is also a lack of obvious anatomical landmarks which makes examination difficult (Bruhn, Van Geffen, Gielen, & Scheffer, 2008). However, successful ultrasound imaging of the sciatic nerve has been reported (Chan et al., 2006; Fornage, 1993; Graif et al., 1991; Heinemeyer & Reimers, 1999; McCartney, Brauner, & Chan, 2004; Ricci, 2005; Schafhalter-Zoppoth et al., 2004; Schwemmer et al., 2005; Schwemmer et al., 2004; Sinha & Chan, 2004; Vloka, Hadžić, April, & Thys, 2001).

There is wide variance of locations reported for USI of the sciatic nerve and its branches. Graif et al. (1991) describe the diameter of the sciatic nerve to range from 5 - 9mm and to be positioned between 2 - 5cm below the skin surface at the posterior mid-thigh (PMT). Heinemeyer and Reimers (1999) scanned the sciatic nerve with ultrasound "in the middle of the dorsal thigh" (p. 482) and the tibial nerve distal to its bifurcation within the popliteal fossa. The accuracy of nerve identification at these locations was reported as 74% (37 of 50 healthy participants) at the mid-dorsal thigh and 20% (10 of 50 healthy participants) at the bifurcation (Heinemeyer & Reimers, 1999).

Other authors have noted higher rates of success, 72% (53 of 74 participants), (Schwemmer et al., 2005) and 100%; 10 of 10 participants (Sinha & Chan, 2004), 15 of 15 participants (Bruhn et al., 2008) and 60 of 60 limbs (Ricci, 2005); for identification of the sciatic nerve. Bruhn et al. (2008) state that the best location to visualise the sciatic nerve is where the skin-nerve distance is the least (i.e. the nerve is closer to the skin). They suggest that the optimal location for scanning is 5.4-10.8cm below the subgluteal crease (Bruhn et al., 2008). Beyond the sciatic bifurcation, the tibial nerve continues as a mid-line extension of the sciatic nerve. It is well visualised on ultrasound imaging at the level of the popliteal crease within the popliteal fossa (Bruhn et al., 2008;

Heinemeyer & Reimers, 1999; McCartney et al., 2004; Ricci, 2005; Schwemmer et al., 2005).

The addition of body movements can allow more easy visualisation and differentiation of the sciatic nerve and its branches, a method recommended for the assessment of the median nerve using USI (Coppieters et al., 2009; Echigo et al., 2008). For example, Schafhalter-Zoppoth et al. (2004) found that by adding passive dorsiflexion of the foot (when imaging the sciatic nerve with the knee in extension) the tibial branch will move superficially (i.e. towards the skin) and medially. With the addition of plantarflexion, the common peroneal branch will also move superficially and laterally. These authors referred to this action as the "seesaw sign" and claim it improves visualisation of the sciatic nerve branches. Schafhalter-Zoppoth et al. (2004) also concluded that in longitudinal imaging, the tibial nerve branch of the sciatic nerve will move towards the foot during ankle dorsiflexion.

2.6.3 Ultrasound imaging assessment of peripheral nerve movement.

2.6.3.1 Frame-by-frame cross-correlation analysis.

Methods of tracking grey speckle features of successive frames of ultrasound footage, in order to quantify soft tissue motion, have been reported within the literature (Bohs & Trahey, 1991; Hein & O'Brien, 1993; Korstanje, Selles, Henk, Hovius, & Bosch, 2009; Korstanje, Selles, Stam, Hovius, & Bosch, 2010b). Dilley et al. (2001) have developed a software package which uses speckle tracking to calulate nerve motion. An ultrasound video loop can be broken into a succession of digital frames which each depict individual pixels across a grey-scale from white to black. When the successive frames are put together in a video sequence it is evident that the speckle

features (i.e. the individual pixels) have moved as a result of tissue movement. Dilley et al. (2001) designed a computer programme that was able to calculate the relative movement of selected pixels between frames by employing a cross-correlation algorithm.

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Figure 6. Graphical representation of frame-by-frame cross-correlation analysis.
A) Rectangular region of interest (ROI) within the median nerve. B) Enlargement of ROI in A. in the top panel then moved onwards by one frame in the bottom panel. C) Plot of the correlation coefficient against the pixel shift. Illustration from Coppieters, M. W., Hough, A. D., & Dilley, A. (2009). Different nerve-gliding exercises induce different magnitudes of median nerve longitudinal excursion: an in vivo study using dynamic ultrasound imaging. *Journal of Orthopaedic and Sports Physical Therapy, 39*(3), p. 167.

The algorithm enables calculation of the correlation coefficient between pixel grey levels, for a selected rectangular frame, or region of interest (ROI), between two adjacent ultrasound images (Figure 6, A). The coordinates of the second successive ROI are offset along the horizontal ultrasound image plane and are shifted by one pixel at a time within a predetermined range (i.e. -10 to 10 pixels) (Figure 6, B). The correlation coefficient (measuring the degree to which two variables are linearly related) is calculated against each individual pixel shift and therefore corresponds to the relative movement between frames (Figure 6, C).

The peak of a quadratic equation, fitted to the maximum three correlation coefficients, allows determination of sub-pixel accuracy. In doing so this further refines the algorithm by more accurately assessing the maximum cross-correlation value. This peak is equivalent to the pixel shift/movement between adjacent frames. Therefore this algorithm establishes that the degree of pixel shift that has the highest associated

correlation coefficient corresponds to and represents the relative movement which is measured.

Any relative vertical pixel shift is also taken into account in the cross-correlation formula. For each horizontal cross-correlation analysis, between two adjacent frames, vertical pixel shift is offset against the horizontal plane within a pre-set range (i.e. -5 to +5 pixels) (Dilley et al., 2001). Relative movement between frames can be calculated by this software for ultrasound footage of up to 100 frames.

This frame-by-frame cross-correlation software package can also take into account any potential movement of the skin relative to the ultrasound transducer. To do this, a relatively static structure or tissue within the field of the image is selected. The selected tissue is often either a facial layer, interosseous membrane, bone or the subcutaneous tissues. The same frame-by-frame cross-correlation analysis is performed (as above); however this time the ROI becomes the static tissue. Any movement detected within this analysis is then subtracted from that seen from the nerve. This equation provides a more specific calculation of the actual nerve movement by removing potential error which may arise from any relative movement of the ultrasound transducer (Figure 7).

During initial analysis of this technique, Dilley et al. (2001) looked at the reliability of measurement of several phantom controls (string and avian nerve) in water-bath trials whereby the phantom controls were moved a specified distance and velocity whilst ultrasound footage was captured in the longitudinal plane. Analysis was then performed *in-vivo* measuring longitudinal median nerve excursion, at the forearm, during wrist and finger movements. Graphical representation of the results determined that the technique was reliable when comparing between 1-3 frame intervals. The accuracy of measurement of the phantom controls was stated to be within 25

micrometres and for the in-vivo controls less that 10% error (i.e. <0.29mm) at 10 frames per second. From these analyses, the authors concluded that the frame-by-frame cross-correlation analysis was an accurate and reliable tool in measuring longitudinal nerve movement (Dilley et al., 2001).
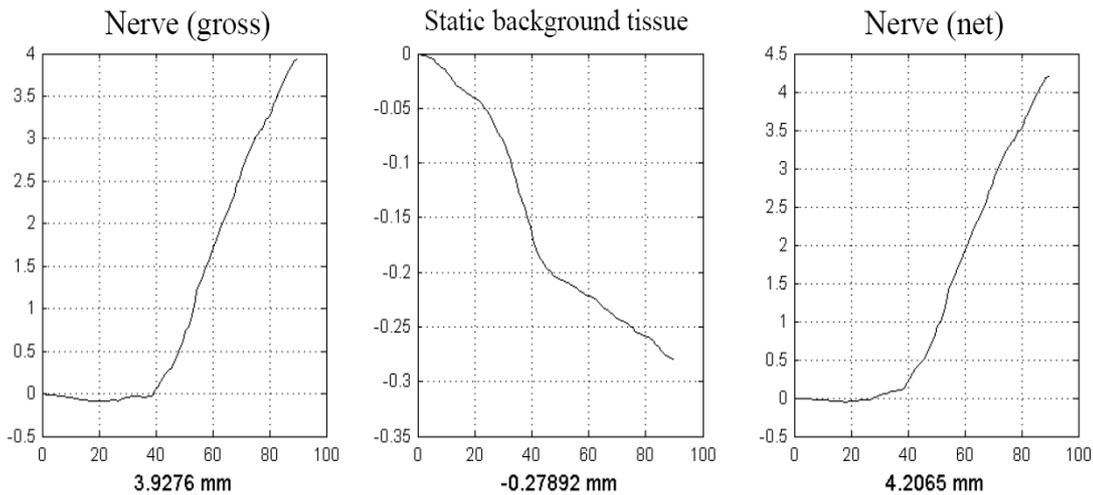
Figure 7. Frame-by-frame cross-correlation analysis of sciatic nerve excursion
Nerve (gross) – cumulative total of nerve movement over three contiguous ROI's. Static background tissue - cumulative total of static tissue movement over three contiguous ROI's. Nerve (net) = Nerve (gross) minus Static background tissue. This analysis was collected as part of this doctoral research.

This method of tissue motion analysis has been utilised for quantification of tendon excursion (Chen, Tsubota, Aoki, Echigo, & Han, 2009; Korstanje et al., 2010a; Korstanje et al., 2009; Korstanje et al., 2010b) and peripheral nerve excursion (Coppieters et al., 2009; Dilley et al., 2003; Dilley et al., 2008; Dilley et al., 2007; Echigo et al., 2008; Erel et al., 2003; Erel et al., 2010; Greening et al., 2005; Greening et al., 2001; Greening et al., 1999; Julius et al., 2004). Several studies have assessed the reliability of measuring peripheral nerve motion *in-vivo*, using this method, and all have observed excellent reliability in measurement of longitudinal nerve excursion (Coppieters et al., 2009; Dilley et al., 2001).

2.6.3.2 Real-time spectral Doppler ultrasound.

Real-time spectral Doppler ultrasound measurement of longitudinal nerve movement has also been described. The Doppler effect refers to a change in frequency of a wave source (i.e. a moving musculoskeletal tissue) due to relative motion (Hough et al., 2000a). This technique employs tracing of the phases of movement of each of the spectral Doppler plots, which are represented by deflections of movement picked up by changes in frequency of the refracted ultrasound wave. Calculations of the area under the deflections yield velocity time integrals (VTI). These are represented along an x-axis within the spectral Doppler sonogram. Deflections above and below the x-axis are representative of the VTI's and give a measurement of nerve movement either in a proximal or distal longitudinal direction. Measurement of the area under each of the deflections allows the VTI to be established (Hough et al., 2000a, 2000b).

Hough et al. (2000b) designed a study to specifically examine the test-retest reliability of using spectral Doppler ultrasound measurement of longitudinal median nerve movement during wrist extension. Measurement was taken over three tests on both arms of sixteen healthy participants. Repeatability of test-retest measurement of longitudinal median nerve movement was reported as having an intra-class correlation coefficient (ICC) of 0.92 (95% CI: 0.87-0.96). The authors concluded that this was a good level of test-retest repeatability for the assessment of median nerve excursion (Hough et al., 2000b).

Hough and colleagues have, however, raised some concerns with regard to this method. For example, imaging of peripheral nerves at sites where there may be relatively more transverse neural movement may take the nerve outside of the spectral Doppler image and therefore create image artefacts (Hough et al., 2000b). However, the same limitation has been reported for other methods attempting to analyse

longitudinal tissue movement (Dilley et al., 2001) and is not unique to the Doppler
method.

Chapter Three. Neural mobilisation: a systematic review of randomised controlled trials with an analysis of therapeutic efficacy

Ellis, R. F., & Hing, W. A. (2008). Neural mobilization: a systematic review of randomized controlled trials with an analysis of therapeutic efficacy. *Journal of Manual & Manipulative Therapy, 16*(1), 8-22.

This paper was awarded runner-up for The 2008 OPTP Award for Excellence in a Published Review of the Literature (awarded by the Journal of Manual and Manipulative Therapy). The article has also been translated and re-printed in Czech and German journals of manual therapy.

Ellis, R., & Hing, W. (2008). Neural mobilization: A systematic review of randomized controlled trials with an analysis of therapeutic efficacy. [Mobilizacje struktur nerwowych – przegląd systematyczny badań z randomizacją i grupą kontrolną oraz analiza skuteczności terapeutycznej]. *Medical Rehabilitation. [Rehabilitacja Medyczna], 12*(2), 34-44.

Ellis, R., & Hing, W. (2009). Neurale mobilisation: Systematischer review randomisierter kontrollierter studien mit einer analyse der therapeutischen wirksamkeit. *Manuelletherapie, 2*, 47-57.

3.1 PRELUDE

In order to ascertain what research had been conducted regarding the use of neural mobilisation, a systematic review of RCTs was conducted to examine the available clinical research regarding neural mobilisation. Prior to this systematic review there has been no previous systematic review published that has examined neural mobilisation.

To date several clinical textbooks (Butler, 1991, 2000, 2005; Shacklock, 2005a) and textbook chapters (Butler et al., 1994; Butler & Slater, 1994; Elvey & Hall, 2004; Shacklock, 1995a) have been published which significantly emphasise the therapeutic use of neural mobilisation. Through these sources, neural mobilisation has been advocated and promoted. In respect to the thesis, this review enabled all previous RCTs that have used neural mobilisation to be collated in order to review research methodologies and resultant implications and to review whether there was available evidence to support the wide theory base regarding neural mobilisation.

3.2 ABSTRACT

Neural mobilisation is a treatment modality used in relation to pathologies of the nervous system. It has been suggested that neural mobilisation is an effective treatment modality, although support of this suggestion is primarily anecdotal. The purpose of this paper was to provide a systematic review of the literature pertaining to the therapeutic efficacy of neural mobilisation. A search to identify randomised controlled trials investigating neural mobilisation was conducted using the key words *neural mobilisation/mobilization, nerve mobilisation/mobilization, neural manipulative physical therapy, physical therapy, neural/nerve glide, nerve glide exercises, nerve/neural treatment, nerve/neural stretching, neurodynamics*, and *nerve/neural*

physiotherapy. The titles and abstracts of the papers identified were reviewed to select papers specifically detailing neural mobilisation as a treatment modality. The PEDro scale, a systematic tool used to critique RCTs and grade methodological quality, was used to assess these trials. Methodological assessment allowed an analysis of research investigating therapeutic efficacy of neural mobilisation. Ten randomised clinical trials (discussed in 11 retrieved articles) were identified that discussed the therapeutic effect of neural mobilisation. This review highlights the lack in quantity and quality of the available research. Qualitative analysis of these studies revealed that there is only limited evidence to support the use of neural mobilisation. Future research needs to re-examine the application of neural mobilisation with use of more homogeneous study designs and pathologies; in addition, it should standardise the neural mobilisation interventions used in the study.

3.3 INTRODUCTION

In the past, *neural tension* was used to describe dysfunction of the peripheral nervous system. More recently, there has been a shift away from a purely mechanical rationale to include physiological concepts such as structure and function of the nervous system. *Neurodynamics* is now a more accepted term referring to the integrated biomechanical, physiological, and morphological functions of the nervous system (Butler, 2000; Shacklock, 1995a, 1995b, 2005a). Regardless of the underlying construct, it is vital that the nervous system is able to adapt to mechanical loads, and it must undergo distinct mechanical events such as elongation, sliding, cross-sectional

change, angulation, and compression. If these dynamic protective mechanisms fail, the nervous system is vulnerable to neural oedema, ischaemia, fibrosis, and hypoxia, which may cause altered neurodynamics (Butler, 2000; Shacklock, 1995b).

When neural mobilisation is used for treatment of adverse neurodynamics, the primary theoretical objective is to attempt to restore the dynamic balance between the relative movement of neural tissues and surrounding mechanical interfaces, thereby allowing reduced intrinsic pressures on the neural tissue and thus promoting optimum physiologic function (Butler, 2000; Butler et al., 1994; Gifford, 1998; Kitteringham, 1996; Shacklock, 1995b, 2005a). The hypothesised benefits from such techniques include facilitation of nerve gliding, reduction of nerve adherence, dispersion of noxious fluids, increased neural vascularity, and improvement of axoplasmic flow (Butler, 2000; Butler et al., 1994; Coppieters et al., 2003b; Gifford, 1998; Kitteringham, 1996; Rozmaryn et al., 1998; Scrimshaw & Maher, 2001; Shacklock, 1995b, 2005a). However, these etiological mechanisms for the clinically observed effects of neural mobilisation still require robust validation. At present, the positive clinically observed effect of neural mobilisation is mainly based on anecdotal evidence. Therefore, the purpose of this paper was to systematically review and assess the therapeutic efficacy of neural mobilisation for treatment of altered neurodynamics through evaluation of appropriate randomised controlled trials (RCTs). It was hypothesised that the findings might guide evidence-based practice in the clinical application of neural mobilisation.

3.4 METHODS

3.4.1 Literature search strategy.

A search to identify RCTs examining neural mobilisation was conducted in March 2007. The following electronic databases were searched: MEDLINE via PubMed (from 1966 onwards), Cumulative Index to Nursing and Allied Health Literature (CINAHL) (from 1982 onwards), the Cochrane Controlled Trials Register in the Cochrane Library (latest edition), SPORT-Discus (from 1830 onwards), Allied and Complementary Medicine Database (AMED) (from 1985 onwards), Physiotherapy Evidence Database (PEDro) (from 1953 onwards), ProQuest 5000 International, ProQuest Health and Medical Complete, EBSCO MegaFile Premier, Science Direct (from 1995 onwards) and Web of Science (from 1945 onwards).

The search strategy of these databases included terms and keywords related to the intervention: *neural mobilisation/mobilization, nerve mobilisation/mobilization, neural manipulative physical therapy, physical therapy, neural/nerve glide, nerve glide exercises, nerve/neural treatment, nerve/neural stretching, neurodynamics* and *nerve/neural physiotherapy. Randomised controlled trial* or RCT was the key term used in relation to the methodology of the studies. The titles and/or abstracts of these citations were reviewed to identify papers specifically detailing neural mobilisation used as a treatment modality. The search was limited to studies written in or translated to English and those utilising human subjects. There was no limitation regarding the date the studies were published, other than the date limitations of each selected database. In addition, the reference lists of each paper were searched to identify other relevant papers.

3.4.2 Study selection.

The method for selection of relevant studies was consistent with suggested guidelines for conducting systematic reviews (van Tulder, Furlan, Bombardier, & Bouter, 2003). The following inclusion criteria were used to select relevant papers for the review:

- Type of participant: participants older than 18, of either gender, and with a clinical diagnosis consistent with neurodynamic dysfunction (musculoskeletal conditions with symptoms of pain and/or paraesthesia indicative of compromise of the peripheral nervous system)

- Type of study design: randomised controlled trials

- Type of intervention: use of a manual or exercise technique designed to have a direct effect on neural tissue with the purpose of dynamically influencing (e.g. sliding, stretching, moving, mobilising, etc.) the neural tissue

- Outcome measurements: at least one of the following outcome measurements used to assess the status of the nervous system: pain rating (e.g. Visual Analogue Scale [VAS], function-specific pain VAS (i.e. work- or sport-related pain), pain and or range of movement (ROM) during neural tissue provocation tests (NTPT), functional disability scores (e.g. Short-form McGill Pain Questionnaire, Northwick Park Questionnaire, and Oswestry Disability Index).

3.4.3 Methodological quality assessment.

Three reviewers independently assessed the methodological quality of each RCT. The PEDro Scale (Table 2), developed by *The Centre of Evidence-Based Physiotherapy* (CEBP), was utilised to assess each paper (CEBP, 2006). The PEDro Scale, an 11-item scale, is a validated, reliable, and versatile tool used to rate RCTs for

the PEDro Database (Clark et al., 1999; Maher, Sherrington, Herbert, Moseley, & Elkins, 2003; Overington, Goddard, & Hing, 2006). The PEDro scale has been used as a measure of methodological quality in many systematic literature reviews (Ackerman & Bennell, 2004; Bleakley, McDonough, & MacAuley, 2004; Hakkennes & Keating, 2005; Harvey, Herbert, & Crosbie, 2002b; O'Shea, Taylor, & Paratz, 2004).

An overall score of methodological quality, or quality score (QS), was determined for each paper by each of the three reviewers as a total of positive scores for 10 of the 11 items (i.e. N/10). Unlike the other items, Criterion One of the PEDro scale relates to external validity and was not used in the final total PEDro score (CEBP, 2006; Maher et al., 2003; Overington et al., 2006). A consensus method was used to discuss and resolve discrepancies between the markings of each paper between the reviewers. The agreed QS for each paper are included in Table 3.

The various items of the PEDro Score deal with different aspects of RCT analysis including internal validity, external validity, and statistics. In order to allow quantitative analysis of the methodological quality of a systematic review, van Tulder et al. (2003) recommended the analysis of the internal validity criteria of any rating tool. For the PEDro Scale, seven items relating to internal validity were identified. These seven items include items 2, 3, and 5 through 9. An internal validity score (IVS) has also been used in other systematic reviews (Reid & Rivett, 2005) to allow calculation of the number of internal validity criteria met for that particular rating system and to thereby give an assessment of methodological quality. It was decided to calculate an IVS for this review based on the relevant internal validity criteria of the PEDro Scale. The positive scores of each of these seven items were added together to calculate the IVS.

Table 2. The PEDro Scale
Modified from Maher, C. G., Sherrington, C., Herbert, R. D., Moseley, A. M., & Elkins, M. (2003). Reliability of the PEDro scale for rating randomised controlled trials. *Physical Therapy, 83*(3), 713-721.

Criteria	Score	
	No	**Yes**
1. Eligibility criteria were specified *		
2. Subjects randomly allocated to groups	NO (0)	YES (1)
3. Allocation was concealed	NO (0)	YES (1)
4. Groups similar at baseline regarding the most important prognostic factors	NO (0)	YES (1)
5. Blinding of all subjects	NO (0)	YES (1)
6. Blinding of all therapists who administered therapy	NO (0)	YES (1)
7. Blinding of all assessors who measured at least one outcome	NO (0)	YES (1)
8. Measures of at least one key outcome were obtained from more than 85% of initially allocated subjects	NO (0)	YES (1)
9. All subjects for whom outcome measures were available received treatment or control as allocated, or if this was not the case, at least one outcome measure analysed using "intention to treat" analysis	NO (0)	YES (1)
10. The results of between-group statistical comparisons are reported for at least one key outcome	NO (0)	YES (1)
11. The study provides both point measures and measures or variability for at least one key outcome	NO (0)	YES (1)
Total		N/10

* Criteria 1 score is not included in the overall PEDro rating.

To stratify methodological quality, the summated score of the 7-item IVS, calculated from the initial PEDro score (QS), was divided into three categories. A study of *high methodological quality* obtained IVS values of 6 - 7, a *moderate quality* obtained IVS values between 4 - 5, and a *limited quality* was scored between 0 - 3. This decision was made based on even cut-off points between 0 and 7.

Table 3. Randomised controlled trials of neural mobilisation as a treatment modality in order of PEDro score

Scores for PEDro Criteria	1*	2	3	4	5	6	7	8	9	10	11	QS	Methodological Quality	IVS
Cleland et al. (2007)	1	1	1	1	0	0	1	1	1	1	1	8	Moderate	5
Coppieters et al. (2003b)	1	1	1	1	0	0	1	1	1	1	1	8	Moderate	5
Tal-Akabi & Rushton (2000)	1	1	1	1	0	0	1	1	1	1	1	8	Moderate	5
Pinar et al. (2005)	1	1	1	1	0	0	1	1	1	1	1	8	Moderate	5
Baysal et al. (2006)	1	1	1	1	0	0	1	1	1	1	1	8	Moderate	5
Allison et al. (2002)	1	1	1	0	0	0	1	1	1	1	1	7	Moderate	5
Coppieters et al. (2003a)	1	1	1	0	0	0	1	1	1	1	0	6	Moderate	5
Akalin et al. (2002)	1	1	0	1	0	0	0	1	1	1	1	6	Limited	3
Scrimshaw & Maher (2001)	1	1	0	0	0	0	1	1	1	1	1	6	Moderate	4
Vicenzino et al. (1996)	1	1	0	0	0	0	1	1	1	1	1	6	Moderate	4
Drechsler et al. (1997)	1	1	0	0	0	0	0	1	1	1	1	5	Limited	3

Note: QS = overall quality score; IVS = internal validity score.

*Criteria 1 score is not included in the overall PEDro rating.

3.4.4 Analysis of therapeutic efficacy.

When RCTs are heterogeneous, there is no available method to quantitatively assess the relative benefit (or lack thereof) of one intervention versus another because the studies may not be comparing similar patient populations or interventions. In situations where the heterogeneity of primary studies prevents use of a quantitative meta-analysis to summarise the results, recommendations are typically made based on a qualitative assessment of the strength of the evidence (Reid & Rivett, 2005). The RCTs reviewed for this paper were considered heterogeneous because they explored a variety of pathologies and different types of neural mobilisation techniques. Consequently, a quantitative meta-analysis was not appropriate and results were analysed in a qualitative fashion. The qualitative assessment used within this review was an adaptation of those used by several authors (Karjalainen et al., 2001; Reid & Rivett, 2005; van Tulder et al., 2003) modified specifically to include the IVS obtained from the PEDro Scale:

- Level 1: Strong evidence: provided by generally consistent findings in multiple RCTs of high quality.

- Level 2: Moderate evidence: provided by generally consistent findings in one RCT of high quality and one or more of lower quality.

- Level 3: Limited evidence: provided by generally consistent findings in one RCT of moderate quality and one or more low-quality RCTs.

- Level 4: Insufficient evidence: provided by generally consistent findings of one or more RCTs of limited quality, or when no RCTs were available, or when studies provided conflicting results.

3.4.5 Clinical benefit.

Lastly, to determine whether a clinical benefit for neural mobilisation could be concluded, a ranking system similar to that used by Linton and van Tulder (2001) was used. A positive effect was concluded if the intervention (i.e. neural mobilisation) was statistically significantly more beneficial compared to the control for at least one key outcome variable, a negative effect if the intervention was less effective than the control, and a neutral effect was concluded where the intervention and control did not statistically differ significantly for any of the outcome variables (Linton & van Tulder, 2001).

3.5 RESULTS

3.5.1 Selection of studies.

Ten RCTs, represented by 11 published articles (Akalin et al., 2002; Allison, Nagy, & Hall, 2002; Baysal et al., 2006; Cleland, Childs, Palmer, & Eberhart, 2007; Coppieters, Stappaerts, Wouters, & Janssens, 2003a; Coppieters et al., 2003b; Drechsler, Knarr, & Snyder-Mackler, 1997; Pinar et al., 2005; Scrimshaw & Maher, 2001; Tal-Akabi & Rushton, 2000; Vicenzino et al., 1996), satisfied the inclusion criteria following the electronic and manual reference list searches. The articles published by Coppieters et al. (2003a, 2003b) are from the same subject group and were thus classified as one RCT. These studies are summarised in Table 5.

3.5.2 Methodological quality.

The methodological quality for each paper, represented by the IVS, is detailed in Table 3. Nine of 11 studies (Allison et al., 2002; Baysal et al., 2006; Cleland et al., 2007; Coppieters et al., 2003a, 2003b; Pinar et al., 2005; Scrimshaw & Maher, 2001; Tal-Akabi & Rushton, 2000; Vicenzino et al., 1996) reviewed were given an IVS of 4 or 5 and were of moderate methodological quality. Two of the studies (Akalin et al., 2002; Drechsler et al., 1997) were given an IVS of 3, suggesting limited methodological quality. Table 4 presents statistics relating to the percentage of each item that was satisfied for an IVS score.

Table 4. Number and percentage of the studies meeting each PEDro criteria

PEDro Criteria	Number meeting criterion (N)	Percent meeting criterion (%)
1. Eligibility criteria specified (yes/no)	11	100
2. Subjects randomly allocated to groups (yes/no)	11	100
3. Allocation was concealed (yes/no)	7	64
4. Groups similar at baseline (yes/no)	6	55
5. Subjects were blinded to group allocation (yes/no)	0	0
6. Therapists who administered therapy were blinded (yes/no)	0	0
7. Assessors were blinded (yes/no)	9	82
8. Minimum 85% follow-up (yes/no)	9	100
9. Intent to treat analysis for at least 1 key variable (yes/no)	9	100
10. Results of statistical analysis between groups reported (yes/no)	9	100
11. Point measurements and variability reported (yes/no)	10	91

All of the 11 studies satisfied the items relating to random allocation of subjects, measures of one key outcome taken from greater than 85% of the population, use of intention-to-treat analysis (where this was required due to a drop-out group), and results of statistical analysis reported (items 2, 8, 9, and 10).

All 11 studies did not satisfy items 5 and 6, which relate to subject and therapist blinding. Two studies (Akalin et al., 2002; Drechsler et al., 1997) did not satisfy item 7, which relates to rater blinding. This suggests that these two studies lacked all three forms of blinding (subject, therapist, and rater). The other 9 studies were single-blinded (rater-blinded) studies. There was no clear trend established for item 4, which relates to concealed allocation of subjects.

3.5.3 Study characteristics.

All ten RCTs used different methods of application of neural mobilisation (e.g. cervical lateral glide, slump sliders, peripheral nerve sliders, etc.), and some studies chose to combine these techniques with home-based neural mobilisation exercises. There were also differing neurodynamic dysfunctions examined, including lateral epicondyalgia, carpal tunnel syndrome, post-operative spinal surgery, non-radicular low back pain, and neurogenic cervico-brachial pain syndrome. Therefore, all ten RCTs were clinically and therapeutically heterogeneous, necessitating a qualitative analysis for summarising the results. Table 5 contains details of study characteristics.

3.5.4 Therapeutic efficacy.

Of the 11 studies identified, 6 different categories or types of treatment were identified (Table 6). Using the qualitative rating system, as mentioned earlier, it appears

there is limited evidence (Level 3) to support the use of neural mobilisation that involves active nerve and flexor tendon gliding exercises of the forearm (Akalin et al., 2002; Baysal et al., 2006; Pinar et al., 2005), cervical contralateral glides (Coppieters et al., 2003a, 2003b; Vicenzino et al., 1996), and Upper Limb Tension Test 2b (ULTT2b) mobilisation (Drechsler et al., 1997; Tal-Akabi & Rushton, 2000) in the treatment of altered neurodynamics or neurodynamic dysfunction. There was inconclusive evidence (Level 4) to support the use of neural mobilisation involving slump stretches (Cleland et al., 2007) and combinations of neural mobilisation techniques (Allison et al., 2002; Scrimshaw & Maher, 2001) in the treatment of altered neurodynamics or neurodynamic dysfunction.

3.5.5 Clinical benefit.

Table 5 lists the study details of the 11 studies. More studies found a positive effect (Akalin et al., 2002; Allison et al., 2002; Baysal et al., 2006; Cleland et al., 2007; Coppieters et al., 2003a, 2003b; Pinar et al., 2005; Vicenzino et al., 1996) than a neutral effect (Drechsler et al., 1997; Scrimshaw & Maher, 2001; Tal-Akabi & Rushton, 2000).

Table 5. Randomised controlled trials of neural mobilisation as a treatment modality

Author	Patient demographics	Intervention Group (IG)	Comparison Group (CG)	Outcome	Result	IVS	QS
Cleland et al. (2007)	N=30 (9 male, 21 female) -Age range 18-60 years -Mean age (years) IG 40.0 (±12.2), CG 39.4 (±11.3) Duration symptoms (weeks) IG 14.5 (±8.0), CG 18.5 (±12.5)	16 subjects with low back pain Same as control plus: Slumped stretching exercise (position held 30 seconds, 5 repetitions) Home exercise slump stretches (2 repetitions for 30 seconds) 2 x week for 3 weeks	14 subjects with low back pain 5-minute cycle warm-up Lumbar spine mobilisation (Posterior-anterior mobilisations to hypomobile lumbar segments, grade 3-4) Standardised exercise program (pelvic tilts, bridging, squats, quadruped alternate arm/leg activities; 2 sets 10 repetitions each exercise) 2 x week for 3 weeks	Outcomes were measured pre- and post-treatment 1. Body diagram (for distribution of symptoms) 2. Numeric pain rating scale (NPRS) 3. Modified Oswestry disability index (ODI) 4. Fear avoidance beliefs questionnaire	No baseline differences between groups (p> 0.05). At discharge, patients who received slumped stretching demonstrated significantly greater improvements in disability (9.7 points on the ODI, p< 0.001), pain (0.93 points on the NPRS, p=0.001), and centralisation of symptoms (p<0.01) than patients who did not. The between-group comparisons suggest that slump stretching is beneficial for improving short-term disability, pain, and centralisation of symptoms.	5	8
Baysal et al. (2006)	N=36 (36 female patients – all with clinical and electrophysiological evidence of CTS All with bilateral involvement Mean age – Group 1 47.8 ± 5.5; Group 2 50.1 ± 7.3; Group 3 51.4 ± 5.2 Mean duration of symptoms (years) – Group 1 1.5 ± 1.6; Group 2 1.4 ± 0.8; Group 3 1.4 ± 0.8 8 eventual dropouts	- **Group 1** - (N=12) custom made neutral volar splint (worn for 3 weeks); exercise therapy (nerve and tendon gliding exercises as described by Totten & Hunter, 1991) 5 sessions daily, each exercise repeated 10x/session –for 3 weeks - **Group 2** - (N=12) custom made neutral volar splint (worn for 3 weeks); Ultrasound (15min/session to palmar carpal tunnel, 1MHz, 1.0w/cm2, 1:4, 5cm2 transducer) 1 Rx/day, every 5 days for 3 weeks (total 15 Rx's)	Experimental groups 1 and 3 that incorporated nerve gliding exercises and a comparison group that did not incorporate these exercises. Comparison between groups 2 and 3 as the only difference in intervention programs was that group 3 used nerve gliding exercises and group 2 did not.	All measures pre-Rx, end of Rx, and 8 weeks F/U 1. pain (VAS) 2. Tinel's sign 3. Phalen's sign 4. mean static two-point discrimination – pulp of radial three digits 5. hand-grip strength – hand-held dynamometer 6. pinch strength – between thumb and little finger – dynamometer 7. symptom-severity scale questionnaire (11 items) 8. functional status scale questionnaire (8 items) 9. median motor nerve conduction – motor distal	No significant differences between groups at the end of Rx and 8 weeks follow-up of all measures of Treatment Effect (measures 1, 5, 6, 7, 8, 9, 10) Within group comparisons showed significant improvement seen in all 3 groups in Tinel's and Phalen's signs at end of Rx and 8 weeks follow-up Significant improvement seen in all 3 groups in grip and pinch strength at 8 weeks follow-up. No changes seen in two-pt discrimination Within-group analysis showed significant improvement in pain,	4	8

		- **Group 3** -(N=12) <u>custom made neutral volar splint</u> (worn for 3 weeks); <u>exercise therapy</u> (nerve and tendon gliding exercises as described by Totten & Hunter, 1991) 5 sessions daily, each exercise repeated 10x/session – continued for 3 weeks; <u>Ultrasound</u> (15minutes/session to palmar carpal tunnel, 1MHz, 1.0w/cm2, 1:4, 5cm2 transducer) 1 Rx/day, every 5 days for 3 weeks (total 15 Rx's)	latency EMG of abductor pollicis 10. sensory distal latency – EMG of abductor pollicis 11. needle EMG of abductor pollicis brevis – looking for denervation 12. patient satisfaction survey (at 8weeks follow-up only)	symptom and functional scales of all three groups at end-Rx and 8 weeks follow-up Group 3 had significantly the best results at 8 weeks follow-up patient satisfaction questionnaire Median sensory distal latency significantly decreased in groups 1 and 3 at end-Rx and 8 weeks follow-up No significant change seen in median motor distal latency of all 3 groups P<0.05 In summary, between-group analysis revealed no difference between groups, but within-group analysis showed that all groups improved a statistically significant amount for a majority of outcome measures.		
Pinar et al. (2005)	N =26 (female) Age range 35-55 years Duration of symptoms (mo) CG 47.6 (± 6.8), IG 49.6 (± 5.2)	14 patients (19 hands) patients diagnosed with early-middle stages CTS In addition to splint wearing and patient training program treated with nerve gliding exercises 10 repetitions 5 sets a day for 10 weeks, combined with a conservative treatment program	12 patients (16 hands) patients diagnosed with early-middle stages CTS Treated in volar splint in neutral worn day & night for 6-weeks, then night only from week 6-10, and a patient training program for the modification of functional activities (avoid repetitive activities, etc.) with a conservative treatment program.	Undertaken before and after a 10-week treatment program. 1. Tinel's Test 2. Phalen's Test 3. Pain (VAS) over a day 4. Motor Function – manual muscle testing, and grip strength (Jamar hand dynamometer) 5. Sensory evaluation (Semmes-Weinstein monofilament [SWM] &2-point discrimination test [2PD]) 6. Electrophysiological test – median & ulnar nerve. distal latencies	Between-group comparisons for these same variables showed no statistically significant differences pre-treatment or post-treatment, so the groups were similar. Both groups made statistically significant improvements in pain, pinch & grip strength, and sensitivity testing according to intra-group or "within-group" analysis (p< 0.05). A statistically significant result favouring the incorporation of neural gliding exercises – with more rapid pain reduction, and greater functional	5	8

Coppieters et al. (2003b) (References described together due to papers' different outcomes on the same subject sample with the same intervention technique).	N=20 (16 females, 4 males) Age range 35- 65 years -Mean age (years) IG 49.1 (±14.1), CG 46.6 (±12.1) -Mean duration of symptoms (mo) IG 2.7, CG 3.2	10 subjects with brachial or cervicobrachial neurogenic pain Received neural mobilisation treatment (contralateral glide of cervical segment)	10 subjects with brachial or cervicobrachial neurogenic pain Received ultrasound dose of 0.5 W/cm², 5 minutes sonation time, 20% size of head 5cm², frequency 1MHz.	Outcomes were measured pre- and post-treatment 1. Elbow extension ROM during NTPT1 2. Pain (VAS) 3. Symptom distribution	Significant differences in treatment effects between two groups could be observed for all outcome measures (p≤0.306). For the mobilisation group, the increase in elbow extension from 137.3° to 156.7°, the 43% decrease in area of symptom distribution and decrease in pain from 7.3 to 5.8 were significant (p≤0003). For ultrasound group, there were no significant differences	5 8
Coppieters et al. (2003a)	As above	Cervical contralateral glide C5-T1. Several components of the neural tension provocation test of the median nerve (NTPT1) were applied. Patients in supine received a lateral translation movement	Pulsed ultrasound for 5 minutes over the most painful area (0.5 W/cm², 1MHz, treatment head 5cm²). Arm was in unloaded position. Ultrasound chosen because it does not involve any movement of peripheral	Measurements taken pre- and post-treatment 1. Elbow extension ROM during NTPT1 2. Pain intensity during the NTPT1 VAS	On the involved side, the shoulder girdle elevation force occurred earlier and the amount of force at the end of the test was substantially though not significantly greater on the uninvolved side at the corresponding ROM. Together with a significant reduction in pain perception after the cervical mobilisations, a clear	5 6

improvement especially in grip strength (p< 0.05).

Tables 2 – 4 provide post-treatment data on electrophysiological, Tinel's, and Phalen's test findings. Since all subjects had "positive/pathologic" findings pre-treatment, the authors could use these 2x2 contingency tables to generate a number needed to treat to see whether there was a clinically important effect favouring neural gliding exercises on these particular outcomes.

Study	Sample	Intervention		Measurements	Results		
			away from their involved side, while mimicking cervical side flexion or rotation. After 2 trials, 3 repetitions were performed.	nerves.	tendency toward normalization of the force curve could be observed, namely, a significant decrease in force generation and a delayed onset. The control group demonstrated no differences.	5	7
Allison et al. (2002)	N=30 (20 females, 10 males) Age range 18-75 years Median duration of symptoms (mo) NT 12 IQR 48 AT 72 IQR 72 CG 12 IQR 91	Neural tissue manual therapy (NT) — Cervical lateral glide, shoulder girdle oscillation, muscle re-education, home mobilisation. For 8 weeks. Articular treatment group (AT) Glenohumeral joint mobilisation, thoracic mobilisation and home exercise. For 8 weeks.	Received no intervention for the initial 8 weeks (Then at the end of the study they were given neural treatment as a cross-over protocol.)	Measurements taken pre-treatment 4 weeks into treatment and post-treatment. 1. McGill pain questionnaire 2. Northwick Park questionnaire 3. Pain (VAS)	Both intervention groups were effective in improving pain intensity, pain quality scores, and functional disability levels. However, a group difference was observed for the VAS scores at 8 weeks with the "neural manual therapy" group having a significantly lower score.	5	7
						3	6
Akalin et al. (2002)	N=36 (2 male, 34 female) Age range 38-64 years Mean age 51.93 ±5.1 years Mean group age (years) CG 52.16 (±5.6), IG 51.7 (±5.5) Duration of symptoms (mo) CG 47.6 (± 6.8), IG 49.6 (± 5.2)	18 subjects with CTS Same as control plus: Tendon glides in 5 positions. Median nerve exercises in 6 positions. (Each position was maintained for 5 seconds; 10 repetitions of each exercise were done 5 times a day) For 4 weeks	18 subjects with CTS Custom-made neutral volar wrist splint was instructed to be worn all night and during the day as much as possible for 4 weeks	Undertaken pre-treatment and 8 weeks post-treatment 1. Phalen's sign 2. Tinel's sign 3. 2-point discrimination 4. Grip strength 5. Pinch strength 6. Symptom severity score 7. Functional status score A patient satisfaction investigation undertaken by telephone 8.3 (± 2.5) months post-treatment	At the end of treatment, within-group analysis showed a significant improvement was obtained in all parameters in both groups. The nerve and tendon glide group had slightly greater scores but the difference between groups was not significant except for lateral pinch strength. A total of 72% of the control group and 93% nerve and tendon slide group reported good or excellent results in the patient satisfaction investigation, but the difference between the groups was not significant. In summary, both groups improved by a statistically significant amount	3	6

				according to within-group analysis comparing before and after treatment, but except for lateral pinch strength, both groups improved a similar amount because between-group analysis revealed no statistically significant differences after treatment While patient satisfaction percentages were higher in the neural mobilisation group, this difference between groups was not statistically significant.		
Scrimshaw & Maher (2001)	N=81 (30 female, 51 male) Mean age (years) IG 55 (±17), CG 59 (±16)	35 subjects undergoing lumbar discectomy (N=9), fusion (N=6) or laminectomy (N=20) Same as control plus neural mobilisation added. Exercises were encouraged for up to 6 weeks post-discharge	46 subjects undergoing lumbar discectomy (N=7), fusion (N=9) or laminectomy (N=30) Standard post-operative care (exercises for lower limb and trunk) Exercises were encouraged for up to 6 weeks post-discharge	Measured at baseline, 6 weeks, 6 months, and 12 months. 1. Global perceived effect (GPE) 2. Pain (VAS) 3. McGill pain questionnaire 4. Québec Disability Scale 5. Straight leg raise 6. Time taken to return to work	All patients received the treatment as allocated with 12-month follow-up data available for 94% of those randomised. There were no statistically significant or clinically significant benefits provided by the neural mobilisations treatment for any outcome.	4 6
Tal-Akabi & Rushton (2000)	N=21 Age range 29-85 years Mean age 47.1 (±14.8) Duration of symptoms (years) 2.3 (±2.5, range 1-3) All subjects are on the waiting list for surgery	**Group 1:** 7 subjects with CTS received ULTT 2a mobilisation **Group 2:** - 7 subjects with CTS received carpal bone mobilisation (anterior-posterior and or posterior-anterior) and a flexor retinaculum stretch	Group 3 7 subjects with CTS received no intervention	All except PRS were taken pre- and post-treatment 1. Symptoms diary (24hr VAS) 2. Functional box scale (FBS) 3. ROM -wrist flexion/extension 4. ULTT2a 5. Pain relief scale (PRS) 6. Continuing on to have surgery	An effect of neural mobilisation on pain demonstrated a statistically significant difference between the 3 groups (p<0.01). However, although this improvement was better than no treatment, it was not superior to the effect that could be achieved with carpal bone mobilisation, with no statistical difference in effectiveness of treatment demonstrated between the two intervention groups.	5 8

	Subjects	Treatment group	Control group	Recorded	Results		
Vicenzino et al. (1996)	N=15 with lateral epicondylalgia (7 male, 8 female) Age range 22.5 - 66 years Mean age 44 ± 2 years Duration of symptoms 8 ± 2 months Range of duration 2-36 months	Treatment group Contralateral glide C5/6 grade 3 with affected arm in a predetermined position Placebo group Manual contact was applied as in the treatment group with patient's arm rested on abdomen but no glide was applied All treatments were applied in 3 lots of 30 seconds with 60-second rest periods	Control group Subject's arm rested on abdomen Subjects received 1 of the 3 treatment conditions for 3 days in a random order.	Recorded immediately before and after treatment 1. ULTT2b (measuring degrees of abduction) 2. Pain-free grip strength (hand held dynamometer) 3. Pressure pain threshold 4. Pain via VAS (over 24 hours) 5. function VAS (over 24hours)	The treatment group produced significant improvements in pressure pain threshold, pain-free grip strength, neurodynamics, and pain scores relative to the placebo and control groups (p< 0.05)	4	6
Drechsler et al. (1997)	N=18 (8 male, 10 female) Age range 30-57 years Mean age 46 years Mean age of groups (years) IG 46.4, CG 45.5	8 subjects with lateral epicondylitis Neural tension group ULTT 2b with.... 1. Graded flexion and or shoulder abduction 2. Anterior-posterior mobilisations of radial head if radial head mobility was judged hypomobile Home exercise plan to mimic ULTT2b 10 repetitions a day increasing but not exceeding 2 sets a day. 2x week for 6-8 weeks	10 subjects with lateral epicondylitis Standard treatment group 2 times a week for 6-8 weeks 1. Ultrasound over common extensor tendon 2. Transverse friction to tendon (1 minute per session) 3. Stretch and strengthen wrist extensors 5-10 repetitions 30 seconds. Dumbbells gradually increasing to 3 sets 15 repetitions 4. Home exercise program stretch and strengthen	Undertaken pre treatment, post treatment and 3 month follow up 1. Self-report questionnaire 2. Grip strength (hand-held dynamometer) 3. Isometric testing extension of 3rd finger 4. ULTT2b (measuring abduction) 5. Radial head mobility (ant/post glides, graded as hypo/normal/hyper 6. Elbow extension ROM during ULTT	Subjects who received radial head mobilisations improved over time (p<0.05) Results from neural tension group were linked to radial head treatment and isolated effects could not be determined. There were no long-term positive results in the standard treatment group.	3	5

Legend: N = number of subjects, IG = intervention group, CG = control group, VAS = visual analogue scale, CTS = carpal tunnel syndrome, Rx = treatment, MHz = mega-hertz, EMG = electromyography, F/U = follow-up, NT = neural treatment, AT = articular treatment, ROM = range of movement, mo = months, yrs = years, ULTT = upper limb tension tests, ant = anterior, post = after, IQR = interquartile range, ULTT2a = median nerve bias neurodynamic test, ULTT2b = radial nerve bias neurodynamic test.

3.6 DISCUSSION

A search to identify RCTs investigating neural mobilisation yielded 11 studies that met the inclusion criteria for this review. Analyses of these studies, using the criteria of Linton and van Tulder (2001), indicated that 8 of the 11 studies (Akalin et al., 2002; Allison et al., 2002; Baysal et al., 2006; Cleland et al., 2007; Coppieters et al., 2003a, 2003b; Pinar et al., 2005; Vicenzino et al., 1996) concluded a positive benefit from using neural mobilisation in the treatment of altered neurodynamics or neurodynamic dysfunction. Three of the 11 studies (Drechsler et al., 1997; Scrimshaw & Maher, 2001; Tal-Akabi & Rushton, 2000) concluded a neutral benefit, which suggests that neural mobilisation was no more beneficial than standard treatment or no treatment. Nine of the 11 studies (Allison et al., 2002; Baysal et al., 2006; Cleland et al., 2007; Coppieters et al., 2003a, 2003b; Pinar et al., 2005; Scrimshaw & Maher, 2001; Tal-Akabi & Rushton, 2000; Vicenzino et al., 1996) reviewed demonstrated moderate methodological quality; the two remaining studies (Akalin et al., 2002; Drechsler et al., 1997) yielded limited methodological quality. Studies exhibited weaknesses in random allocation, intention to treat, concealed allocation, and blinding; consequently, our ability to review and assess the therapeutic efficacy of neural mobilisation for treatment of altered neurodynamics through evaluation of appropriate randomised controlled trials was substantially limited.

Methodological weaknesses can lead to over- or under-estimations of actual outcomes. For example, blinding can significantly eliminate bias and confounding, and is essential in maintaining the robustness of a RCT. Blinding is difficult for use in studies involving manual therapy (Beaton, Boers, & Wells, 2002; Salaffi, Stancati, Silvestri, Ciapetti, & Grassi, 2004), and in this review only 9 of the 11 studies blinded the raters. Some have argued that blinding for use in manual therapy studies is useful

(Beaton et al., 2002), although it is arguable that non-masked raters could bias outcome findings.

The outcome measures used by the RCTs in this review also lacked homogeneity. A battery of different scales was used, and findings are not transferable across populations. One method used to standardise measures of success is the use of a minimal clinically important difference score (MCID). MCID relates to the smallest change in a clinical outcome measure, which correlates to a person feeling "slightly better" than the initially recorded state (Salaffi et al., 2004). Findings can be dichotomised into success or failure. In research that analyses the therapeutic benefit of an intervention, the MCID is an important statistic, as it represents a level of therapeutic benefit significant enough to change clinical practice (Beaton et al., 2002). MCIDs are population- and pathology-specific, and they require analysis to determine a properly computed value. To our knowledge, all or a majority of the outcome scales used have not been evaluated for an MCID for the population examined in our study.

Due to the heterogeneity in respect to the neural mobilisation interventions used in these RCTs, it is difficult to make general conclusions regarding neural mobilisation as a general therapeutic tool. Over all, six different categories or types of neural mobilisation treatments were identified (Table 6). Of these, there was limited evidence to support the use of active nerve and flexor tendon gliding exercises of the forearm (Akalin et al., 2002; Baysal et al., 2006; Pinar et al., 2005), cervical contralateral glides (Coppieters et al., 2003a, 2003b; Vicenzino et al., 1996), and Upper Limb Tension Test 2b (ULTT2b) mobilisation (Drechsler et al., 1997; Tal-Akabi & Rushton, 2000) in the treatment of altered neurodynamics or neurodynamic dysfunction. There was inconclusive evidence to support the use of slump stretches (Cleland et al., 2007) and

combinations of neural mobilisation techniques (Allison et al., 2002; Scrimshaw & Maher, 2001) in the treatment of altered neurodynamics or neurodynamic dysfunction.

Table 6. Level of evidence for therapeutic efficacy per intervention type

Number	Type of Intervention	Studies per Intervention	Evidence for Intervention
1	Slump stretches	Cleland et al. (2007)	Insufficient (Level 4)
2	Active nerve and flexor tendon gliding exercises (forearm)	Baysal et al. (2006) Pinar et al. (2005) Akalin et al. (2002)	Limited (Level 3)
3	Cervical contralateral glide (nerve mobilisation)	Coppieters et al. (2003b) Coppieters et al. (2003a) Vicenzino et al. (1996)	Limited (Level 3)
4	Combination (neural tissue manual therapy, cervical lateral glide, and shoulder girdle oscillations)	Allison et al. (2002)	Insufficient (Level 4)
5	Combination (Straight leg raise, knee flexion/extension, and passive cervical flexion)	Scrimshaw & Maher (2001)	Insufficient (Level 4)
6	Upper limb tension test 2b (ULTT 2b) neural mobilisation	Tal-Akabi & Rushton (2000) Drechsler et al. (1997)	Limited (Level 3)

Future studies are needed and a larger, more comprehensive body of work is required before conclusive evidence is available. Only 10 RCTs met the inclusion criteria for this systematic review. Unfortunately, all were clinically heterogeneous in that they looked at a number of different pathologies and different types of neural mobilisation. This made quantitative analysis of therapeutic efficacy impossible. As Reid and Rivett (2005) have stated, direct quantitative comparison, within the realms of systematic review, is very difficult when pathologies, interventions, and outcome measures are heterogeneous. For example, even for this review there were a number of

studies that looked at neural mobilisation in treatment for lateral epicondyalgia (Drechsler et al., 1997; Vicenzino et al., 1996), carpal tunnel syndrome (Akalin et al., 2002; Baysal et al., 2006; Pinar et al., 2005; Tal-Akabi & Rushton, 2000), and cervicobrachial pain (Allison et al., 2002; Coppieters et al., 2003a, 2003b). The specific neural mobilisation intervention differed between studies, making, in these cases, the treatments too heterogeneous for statistical pooling.

With respect to the clinical implications of these findings, it is interesting to note that generally all the RCTs that invesitgated neural mobilisation for upper quadrant (i.e. cervical spine, shoulder girdle, and upper limb) problems, with the exception of one study (Allison et al., 2002), concluded that there was limited evidence for therapeutic efficacy. This is in direct contrast to studies that examined neural mobilisation for lower quadrant (i.e. lumbar spine, pelvic girdle, and lower limb) problems (Allison et al., 2002; Cleland et al., 2007; Scrimshaw & Maher, 2001) in that all provided inconclusive evidence for therapeutic efficacy. From a more specific pathological perspective, for neural mobilisation of cervical nerve roots, three papers supported the use of cervical contralateral glide mobilisation. For neural mobilisation of the median nerve in people with carpal tunnel syndrome, three papers supported the use of active nerve and flexor tendon gliding exercises of the forearm (Akalin et al., 2002; Baysal et al., 2006; Pinar et al., 2005).

3.6.1 Future research.

Considering the results of the extensive literature search carried out for this review, there is an obvious paucity of research concerning the therapeutic use of neural mobilisation. Not only is there a lack in quantity of such research, upon dissection of the

scarce research that is available, there is also a lack of quality. Future research should look not only at similar pathologies but also at similar neural mobilisation techniques.

Another key feature of these studies is that only clinical outcome measures were used. In the introduction, we discussed the biomechanical, physiological, and morphological theories underlying neural mobilisation. One of the key theories for using neural mobilisation is to exploit the mechanical effect that this form of mobilisation has on the neural tissue and its mechanical interface. It is possible to use objective *in-vivo* measurements of neural movement (i.e. glide, slide, stretch, etc.) via real-time diagnostic ultrasound. It will be important to eventually substantiate clinical improvements with objective measurement of neural movement. For example, recent unpublished data have demonstrated that it is possible to visualise and quantify, with reasonable reliability, sciatic nerve movement during neural mobilisation (Ellis, 2007). As it has been postulated that an improvement in nerve mobility may explain any perceived benefits of neural mobilisation, it would be relevant to make a comparison of clinical measures with objective measures (e.g. ROM and neural mobility) in an *in-vivo* situation in studies that examine neural mobilisation. Such a comparison may give clues as to whether neural mobilisation is more likely to impose a mechanical effect or a neurophysiological effect on the nervous system.

3.7 CONCLUSION

Neural mobilisation is advocated for treatment of neurodynamic dysfunction. To date, the primary justification for using neural mobilisation has been based on a few clinical trials and primarily anecdotal evidence. Following a systematic review of the literature examining the therapeutic efficacy of neural mobilisation, 10 RCTs discussed in 11 studies were retrieved. A majority of these studies concluded a positive therapeutic benefit from using neural mobilisation. However, in consideration of their

methodological quality, qualitative analysis of these studies revealed that there is only limited evidence to support the use of neural mobilisation. Future research needs to examine more homogeneous studies (with regard to design, pathology, and intervention), and we suggest that they combine clinical outcome measures with *in-vivo* objective assessment of neural movement.

REFERENCES

References for this paper can be found in the Reference list at the back of the published paper (see Appendix 9). The references for this paper have also been included in the full reference list of this thesis.

Chapter Four. Reliability of measuring sciatic and tibial nerve movement with diagnostic ultrasound during a neural mobilisation technique

4.1 PRELUDE

The systematic review highlighted the heterogeneity of research methodology across those RCTs which have examined neural mobilisation. In particular, methodological heterogeneity was evident in regard to the neural mobilisation exercises that were selected. What was also apparent is that none of the RCTs assessed the influence of the neural mobilisation exercises on *in-vivo* nerve movement, a key premise of these techniques.

It is imperative to quantify nerve movement during neural mobilisation as they are often used to influence nerve movement. With the availability of USI, *in-vivo* assessment of peripheral nerve mechanics is now viable. Several studies have concluded that this method is reliable in the assessment of median nerve movement (Coppieters et al., 2009; Dilley et al., 2001). However, this has not been concluded for the assessment of lower limb nerve movement.

The second aim of this thesis was to investigate the reliability of using USI to quantify sciatic nerve excursion during a sitting neural mobilisation exercise designed to influence the sciatic nerve. Establishing the high reliability of such methods in the lower limb is important to validate its use as an outcome measure to quantify nerve movement.

4.2 ABSTRACT

Diagnostic ultrasound provides a technique whereby real-time, *in-vivo* analysis of peripheral nerve movement is possible. This study measured sciatic nerve movement during a 'slider' neural mobilisation technique (ankle dorsiflexion/plantarflexion and cervical extension/flexion). Transverse and longitudinal movement was assessed from still ultrasound images and video sequences by using frame-by-frame cross-correlation software.

Sciatic nerve movement was recorded in the transverse and longitudinal planes. The amount of sciatic nerve movement was as much as 12.3mm and 8.6mm in each respective plane. The reliability of ultrasound measurement of transverse sciatic nerve movement was fair to excellent (ICC = 0.39 – 0.76) and excellent (ICC = 0.75) for analysis of longitudinal movement. Therefore this study provides further evidence that diagnostic ultrasound is a feasible, non-invasive, real-time, *in-vivo* method for analysis of sciatic nerve movement.

Keywords

4.3 INTRODUCTION

Diagnostic ultrasound presents an important tool in the study of neurodynamics. Neurodynamics is a term that refers to the integrated biomechanical and physiological functioning of the nervous system (Butler, 2000; Shacklock, 1995b, 2005a), i.e. the ability for a peripheral nerve to slide and stretch in order to accommodate changes in its bed length during joint movements.

Neural mobilisation is a clinical technique that attempts to, amongst other goals, restore normal neurodynamics in conditions where nerve sliding may be affected. Neural mobilisation exercises are well documented within the literature (Cleland et al., 2007; Coppieters et al., 2004; Coppieters & Butler, 2008; Herrington, 2006; Scrimshaw & Maher, 2001; Shacklock, 2005a; Totten & Hunter, 1991). A large number of studies examining neural mobilisation have used cadavers (Beith et al., 1994; Coppieters & Butler, 2008; LaBan, MacKenzie, & Zemenick, 1989; Szabo et al., 1994; Wright et al., 1996). The dissection and removal of certain tissues, required for the examination of neural mobilisation, and embalming techniques in cadavers may alter neural mechanics compared to *in-vivo*. Diagnostic ultrasound therefore offers a potentially portable and non-invasive method for the assessment of peripheral nerve movement. Diagnostic ultrasound has a distinct advantage over other static imaging methods (i.e. magnetic resonance imaging) with its ability to measure soft tissue movement both in real-time and *in-vivo* (Chiou et al., 2003; Hashimoto et al., 1999; Jeffery, 2003; Martinoli et al., 2000).

Several research groups have developed techniques to utilise real-time ultrasound imaging to assess both transverse (Greening et al., 2001) and longitudinal peripheral nerve movement *in-vivo* (Dilley et al., 2001; Hough et al., 2000b). Methods for measuring longitudinal movement have utilised Doppler ultrasound (Hough et al.,

2000a, 2000b) as well as frame-by-frame cross-correlation analysis of high frequency ultrasound image sequences (Dilley et al., 2001; Dilley et al., 2003). Most of the previous studies that have used diagnostic ultrasound to measure peripheral nerve movement have examined nerves in the upper limb (Dilley et al., 2003; Dilley et al., 2007; Erel et al., 2003; Greening et al., 2005; Greening et al., 2001; Hough et al., 2000a, 2000b; Hough, Moore, & Jones, 2007b). In contrast, the present study uses diagnostic ultrasound to measure movement of the sciatic nerve in response to a neural mobilisation exercise, consisting of cervical extension combined with ankle dorsiflexion. Calculations of longitudinal nerve motion were performed using frame-by-frame cross-correlation analysis. The key aims of the present study were to assess the reliability of measuring sciatic nerve movement, both in longitudinal and transverse planes, using diagnostic ultrasound and frame-by-frame cross-correlation analysis.

4.4 MATERIALS AND METHODS

4.4.1 Subjects.

Twenty-seven subjects (fourteen females, thirteen males), with an age range between 18 – 38 years (average = 22.82 years, SD 4.61), were included in this study. Informed consent to participate in this study was given by all subjects. Subjects met the inclusion criteria if they were healthy individuals between the ages of 18-40 and did not have a history of significant/major trauma or surgery to the lumbar, hip, buttock (gluteal) or hamstring (posterior thigh) regions, symptoms consistent with sciatic nerve impairment (i.e. paraesthesias, weakness, etc.), or a positive slump test (a test which determines dysfunction of the sciatic nerve and its associated branches) as described by Butler (2000).

4.4.2 Equipment and procedures.

4.4.2.1 Subject set-up.

A KinCom dynamometer (Kinetic Communicator, Chattex Corp., Chattaneoga, TN, USA) system was used to provide a consistent, fixed and supported subject position. Subjects were seated, with the seat back upright (resting against an additional back support) and the pelvis fixed using a lap seatbelt. This set-up provided a consistent and stable sitting position for all subjects (Figure 8).

In all subjects the right leg was imaged. The mid aspect of the right calf was supported using a wooden support arm. The hip and knee joints were held at 90° and 50° flexion respectively (Figure 8). The angle of each joint position was determined with the use of a goniometer.
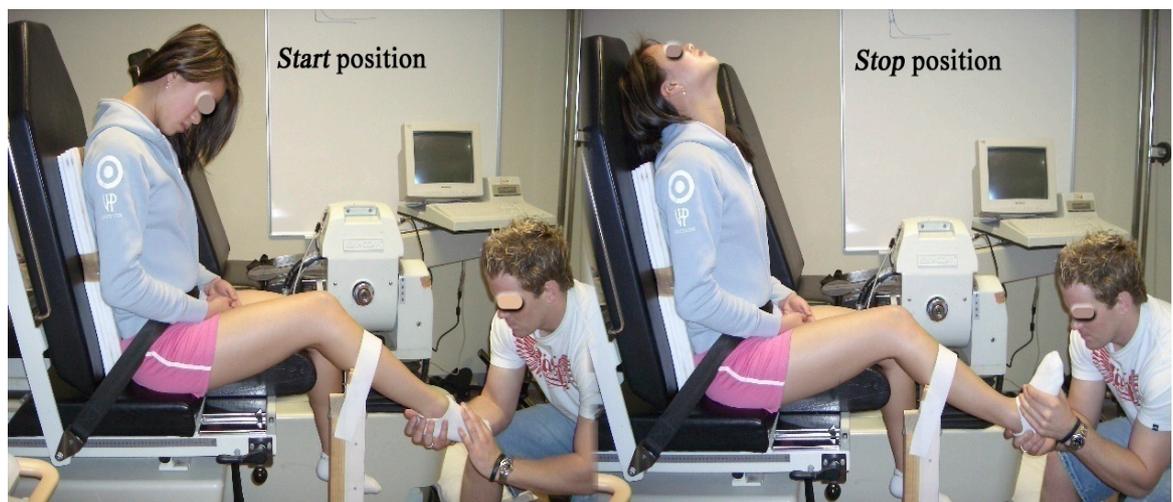
Figure 8. 'Slider' neural mobilisation sequence and participant set-up position.

4.4.2.2 Diagnostic ultrasound parameters and imaging.

An experienced sonographer performed all ultrasound scans. The sonographer was blinded to all ultrasound measurements taken.

B-mode real time ultrasound scanning was performed using a Philips HD11 (Philips Medical Systems Company, Eindhoven, The Netherlands) ultrasound machine with a 5-12 MHz, 55mm, linear array transducer. The sciatic nerve was scanned in both the transverse and longitudinal planes at two separate locations, the posterior mid-thigh (PMT) and popliteal crease (PC).
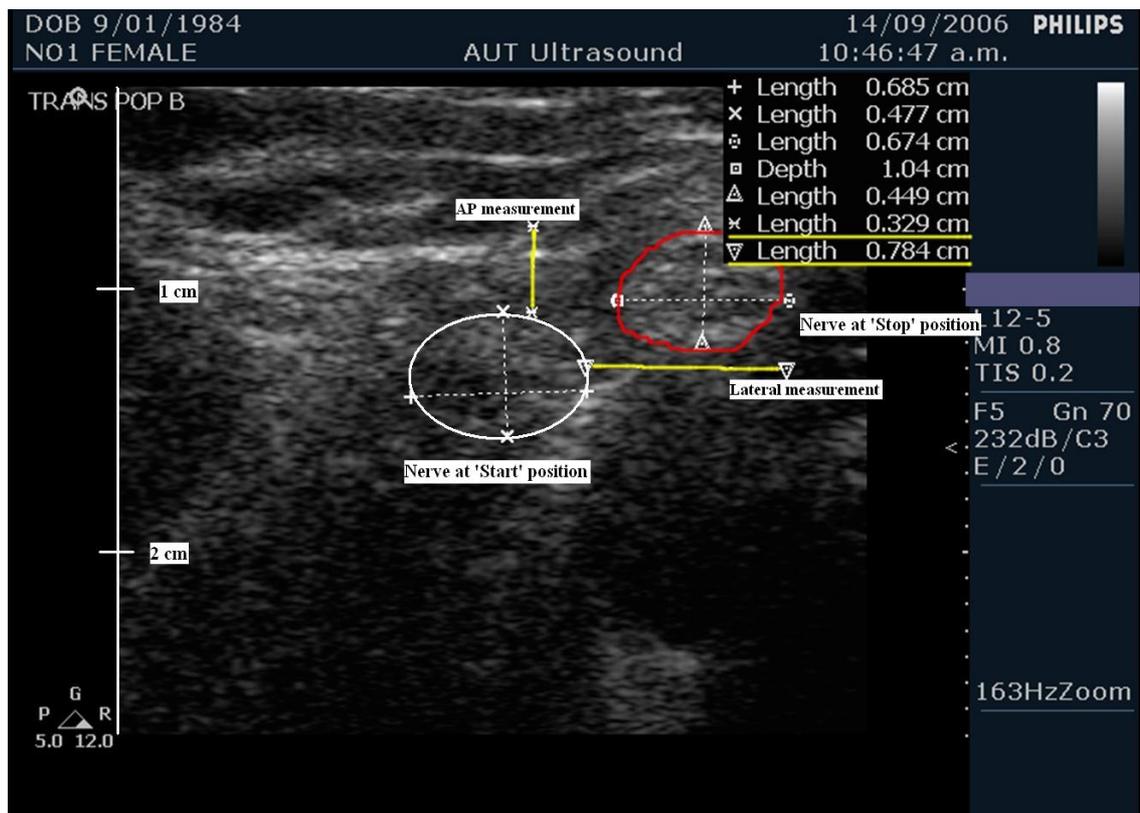
Figure 9. Measurement of transverse movement of the sciatic nerve at the posterior mid-thigh

1. Transverse movement: a static ultrasound image (Figure 9) was taken at the *Start* position of the neural mobilisation exercise**.** At this position, the neck was in full flexion (i.e. chin on the chest) with the ankle joint in full plantarflexion. Within the ultrasound image, digital markers were placed at the lateral-medial and anterior-to-

posterior (AP) extremities/boundaries of the visualised nerve. Measurements of the location of the nerve were recorded.

During the neural mobilisation, active extension of the neck, to a maximum tolerable extension (e.g. 40-70° from neutral), was performed simultaneously with passive dorsiflexion of the ankle until maximum tolerable dorsiflexion (e.g. 20-40° from neutral). At this *Stop position* a second static ultrasound image was taken. Digital markers were again placed at the lateral-medial and AP extremities of the visualised nerve.

Digital callipers were used to measure the vertical/anterior-posterior distance ('AP' movement) between the posterior markers on the *Start* and the *Stop* positions. The same procedure was also used to measure the distance between the right side lateral markers on the *Start* to the *Stop* position to represent the medial-lateral distance ('Lateral' movement) (Figure 9).

A total of three successive measurements were taken at one minute intervals. All measurements were taken by the same sonographer.

2. Longitudinal movement: an ultrasound cine-loop of the nerve in longitudinal plane was recorded from the *Start* to the *Stop* position. The video loop was captured over a one-second period at 40 frames per second. A total of three successive measurements were recorded at one minute intervals.

4.4.2.3 Frame-by-frame cross-correlation algorithm and calculation software.

Each video loop of the longitudinal nerve movement was converted to digital format (bitmaps) and analysed off-line using a method of frame-by-frame cross-correlation analysis that was developed in Matlab (Mathworks, USA) by Dilley et al. (2001). This method employs a cross-correlation algorithm to determine relative movement between successive frames in a sequence of ultrasound images (Dilley et al., 2001). From the initial frame of the sequence, three rectangular regions of interest (ROI) were selected over the sciatic nerve. During the analysis, the program compares the grey-scale values from the ROI's between adjacent frames of the image sequence. In the compared frame, the coordinates of the ROI are offset along the horizontal image plane a pixel at a time within a predetermined range. A correlation coefficient is calculated for each individual pixel shift. The peak of a quadratic equation fitted to the maximum three correlation coefficients is equivalent to the pixel shift/movement between adjacent frames (Dilley et al., 2001). Pixel shift measurements for the nerve were offset against (subtracted from) pixel shifts measurements within the same ultrasound field, from stationary structures (i.e. subcutaneous layers, bone, etc.). This method allows for any slight movement of the ultrasound transducer to be eliminated from the analysis.

4.4.3 Statistical analysis.

Intraclass correlation coefficients (ICC) were calculated as an indication of the reliability of both transverse and longitudinal sciatic nerve movement analysis at the PMT and PC. Bland-Altman plots have been used to provide graphical representation of some of the key reliability findings.

As a measure of combined transverse nerve movements basic trigonometry (Pythagoras' theorem) was used to calculate the diagonal distance of nerve movement, or hypotenuse distance, between the *Start* and *Stop* positions. This particular movement was also quantified in terms of the direction of the movement (i.e. superomedial, superolateral, inferomedial, inferolateral).

Paired T-tests were utilised to explore statistical differences of sciatic nerve measurements between different movement directions and also between different scanning locations.

4.4.4 Ethics.

Ethics approval was sought and approved by AUTEC (Auckland University of Technology Ethics Committee) (see Appendix 3).

4.5 RESULTS

4.5.1 Transverse ultrasound imaging of lateral and anterior-to-posterior sciatic nerve *movement.*

Data representing the transverse sciatic nerve movements measured at the PMT and PC are presented in Table 7 and Figure 10.

At the PMT, the range of lateral movement following the neural mobilisation was $0.01 - 12.30$mm, with a mean value of 3.54mm (SEM ±1.18mm). This compares to AP movement which ranged from $0.02 - 4.19$mm with a mean value of 1.61mm (SEM ±0.78mm). Paired T-tests concluded a statistically significant difference between lateral and AP measurements at the PMT ($P<0.05$).

With respect to the direction of the nerve movement, in 78% of scans at the PMT the nerve moved superiorly (i.e. towards the skin) and medially, 9% moved superior-laterally, 11% inferior (i.e. away from the skin) and medially and 2% inferior-lateral (Figure 11).

At the PC scanning location, the range of lateral movement, during the neural mobilisation, was 0.31 − 10.90mm, with a mean value of 6.62mm (SEM ±1.10mm). This compares to AP movement which ranged from 3.00 − 8.28mm with a mean value of 3.26mm (SEM ±0.99mm). Paired T-tests concluded a statistically significant difference between these measurements at the PC ($P<0.05$).

There was a significant reduction in lateral movement at the PMT (mean = 3.54mm) compared to the PC (mean = 6.62mm; $P<0.05$). There was also a significant reduction in AP movement at the PMT (mean = 1.61mm) compared to the PC (mean = 3.26mm; $P<0.05$).

With respect to the direction of the nerve movement, in 100% of scans at the PC the nerve moved superiorly (i.e. towards the skin) and medially (Figure 12).

Measurements of transverse sciatic nerve movement were possible across all twenty-seven subjects.

Table 7. Amount of sciatic nerve movement (mm) measured for each direction at each scanning location.
All figures representative of data collected from 27 subjects (n=27) aside from those in *Italics* (n=3)

Direction of Sciatic Nerve Movement

| | Transverse | | | | | | Longitudinal | | |
| | AP | | | Lateral | | | | | |
Scanning location	Range	Mean	SEM	Range	Mean	SEM	Range	Mean	SEM
Posterior mid-thigh (PMT)	0.02 - 4.19	1.61	0.62	0.01 - 12.30	3.54	1.01	0.45 - 8.61	3.47	0.75
Popliteal fossa/crease (PC)	3.00 - 8.28	3.26	0.85	0.31 - 10.90	6.62	1.38	*0.71 - 7.60*	*5.22*	*0.48*

Abbreviations: mm = millimetre, n = number of subjects, AP = anterior-to-posterior, SEM = standard error of measurement

Table 8. Intraclass correlation coefficients (ICC) of test-retest reliability for each direction of nerve movement at each scanning location
All figures representative of data collected from 27 subjects (n=27) aside from those in *italics* (n=3)

Direction of Sciatic Nerve Movement

| | Transverse | | | | Longitudinal | |
| | AP | | Lateral | | | |
Scanning location	ICC	95% CI	ICC	95% CI	ICC	95% CI
Posterior mid-thigh (PMT)	0.392	0.154 - 0.625	0.758	0.600 - 0.871	0.753	0.593 - 0.868
Popliteal fossa/crease (PC)	0.560	0.335 - 0.750	0.697	0.510 - 0.837	*0.970*	*0.732 - 0.999*

Abbreviations: mm = millimetre, n = number of subjects, AP = anterior-to-posterior, SEM = standard error of measurement, CI = confidence interval

4.5.2 Longitudinal ultrasound imaging of sciatic nerve movement.

Data representing the longitudinal sciatic nerve movement measured at the PMT and PC are presented in Table 7 and Figure 10.

At the PMT scanning location, the range of longitudinal movement during the neural mobilisation was 0.45 – 8.61mm, with a mean value of 3.47mm (SEM ±0.79mm; n = 27). This compares to longitudinal movement measured at the PC, which ranged from 0.71 – 7.60mm with a mean value of 5.22mm (SEM ±0.05mm; n = 3). There was a statistically significant difference between the two different scanning locations (PMT and PC) for longitudinal movement ($P<0.05$).

With respect to the direction of the nerve movement, in 100% of scans at both the PMT and PC the nerve moved distally.
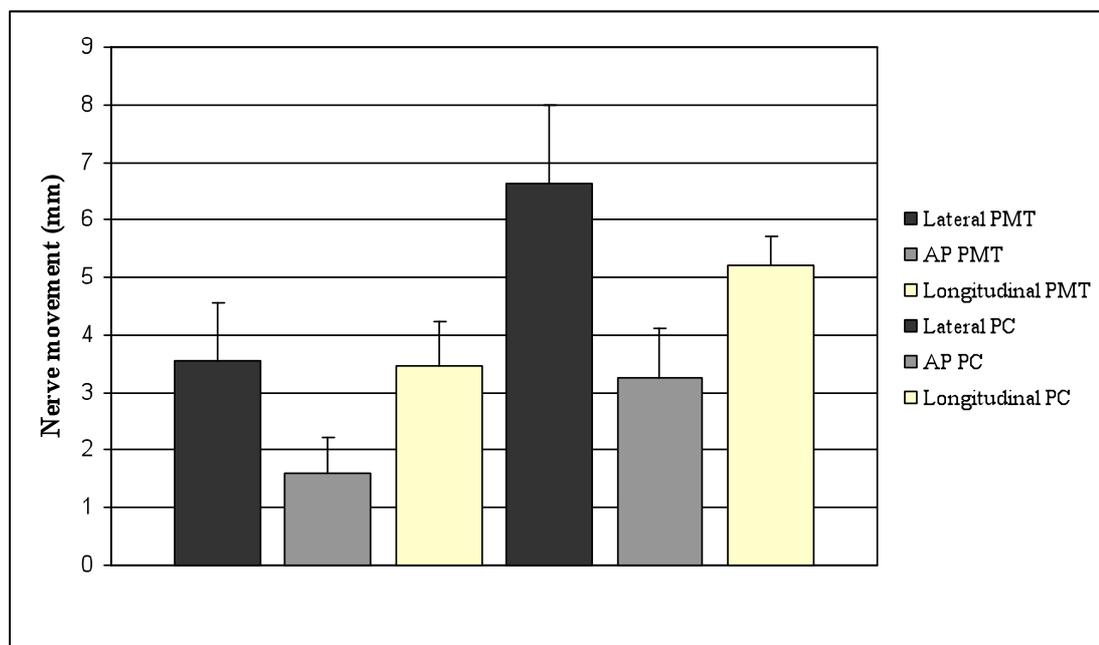
Figure 10. Comparison of sciatic nerve movement at each scanning location
Transverse movement = Lateral and anterior-posterior (AP). PMT: posterior mid-thigh. PC: popliteal crease (Standard error of measurement (SEM) bars included).
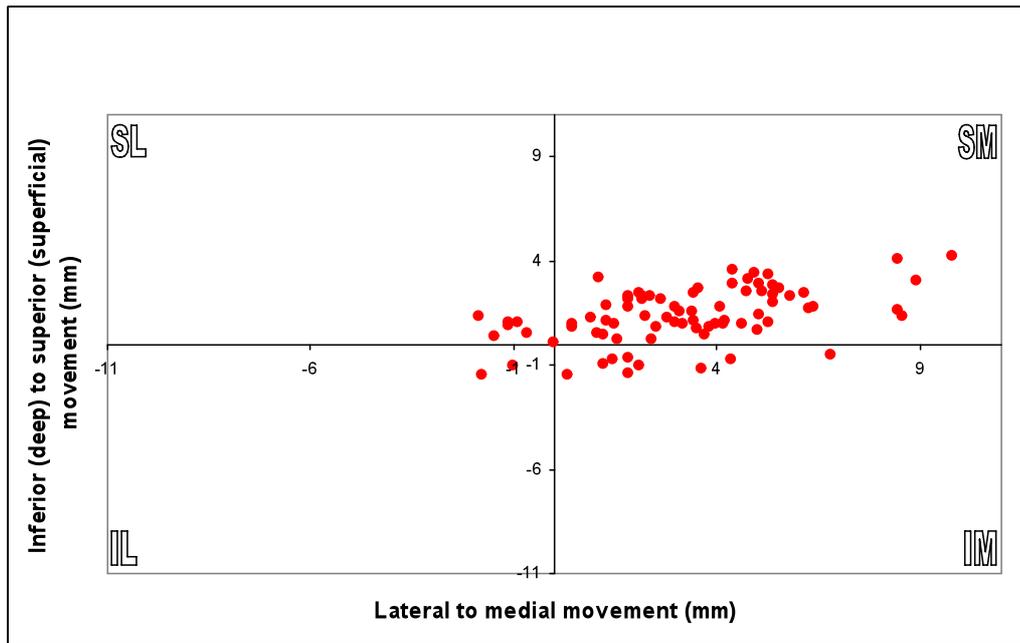
Figure 11. Direction of transverse sciatic nerve movement at the posterior mid-thigh.
SM = superior-medial, SL = superior-lateral, IM = inferior-medial, IL = inferior-lateral
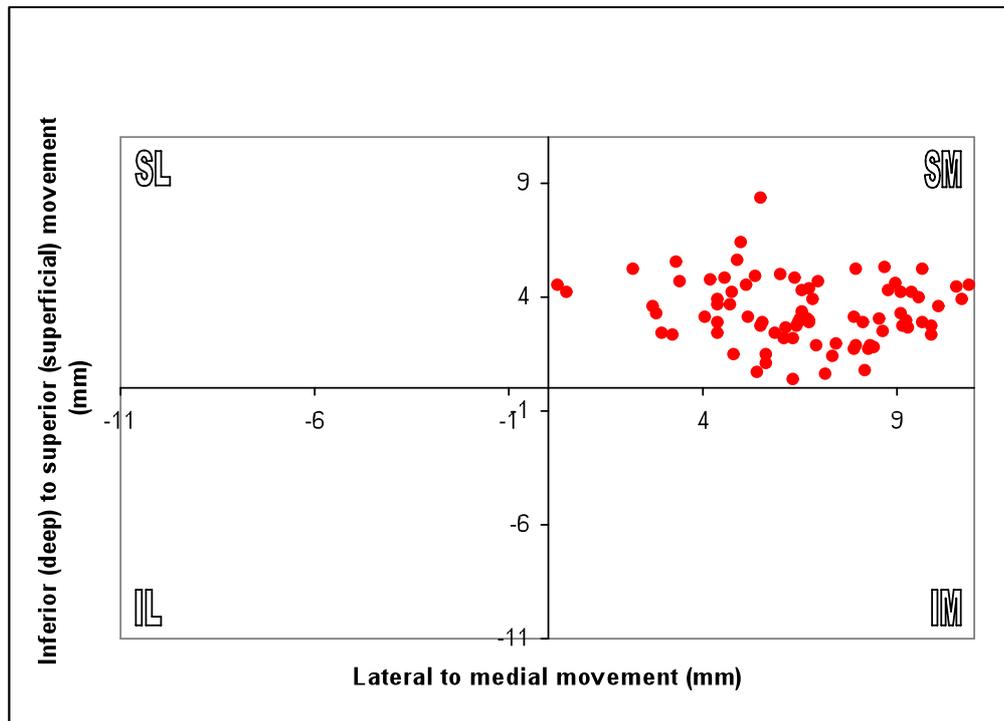
Figure 12. Direction of transverse sciatic nerve movement at the popliteal crease.
SM = superior-medial, SL = superior-lateral, IM = inferior-medial, IL = inferior-lateral

5.5.3 Reliability of diagnostic ultrasound assessment of sciatic nerve movement.

The reliability of sciatic nerve movement recorded at the PMT resulted in an ICC, across three trials for each of the twenty-seven subjects, of 0.76 for lateral sciatic movement, compared to 0.39 for AP movement (Table 10). Bland-Altman plots representing these analyses (comparing the difference between the results plotted against their average) are represented in Figure 17 and 7 respectively.

The reliability of sciatic nerve movement recorded at the PC resulted in an ICC of 0.70 for lateral sciatic movement, compared to 0.56 for AP movement (Table 10).

The reliability of longitudinal sciatic nerve movement recorded at the PMT (n = 27) resulted in an ICC of 0.75 (Figure 18). However because data could only be recorded from three subjects (n=3) for longitudinal movement at the PC is not appropriate to calculate an ICC on such a small subject number (Table 10).
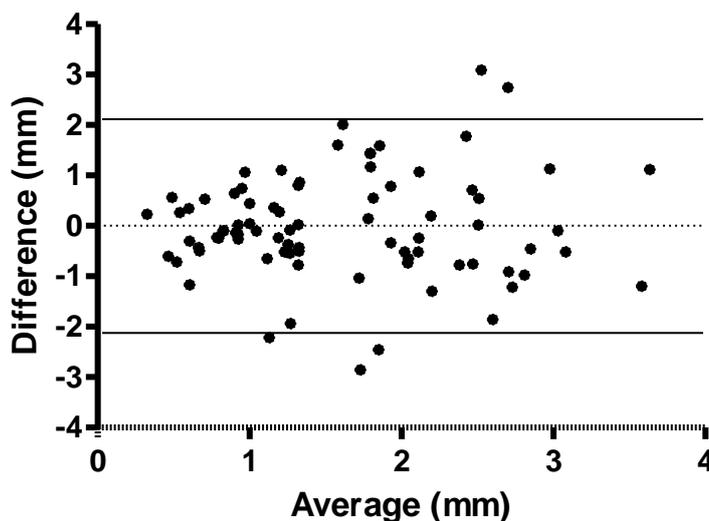
Figure 13. Bland-Altman graph (Difference vs. Average) for all trials measuring AP sciatic nerve movement at the PMT.
Bolded line indicates Limits of Agreement (95%).
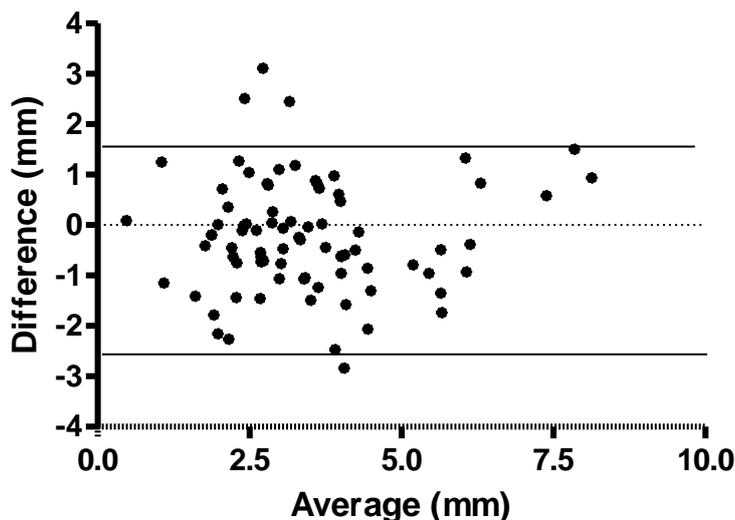
Figure 14. Bland-Altman graph (Difference vs. Average) for all trials measuring longitudinal sciatic nerve movement at the PMT.
Bolded line indicates Limits of Agreement (95%).

5.6 DISCUSSION

Diagnostic ultrasound assessment of peripheral nerve movement is useful in order to establish the extent of neural movement in both the normal and pathological situation. In the present study, sciatic nerve movement was measured using diagnostic ultrasound, a technique that has mainly been used to examine nerve movement in the upper limb (i.e. median and ulnar nerves). This study sought to determine the reliability of this technique for measuring sciatic nerve movement, and to make comment of sciatic nerve movement during neural mobilisation.

Intraclass correlation coefficients were determined as a measure of reliability (Table 10). Generally, an ICC below 0.40 represents poor reliability, $0.40 - 0.75$ represents fair reliability and above 0.75 represents excellent reliability (Fleiss, 1986).

The reliability of the lateral component of the transverse nerve movement was considered excellent at the PMT (ICC = 0.76). However, the reliability of the lateral

component at the PC and the AP component at both the PMT and PC was considered to be fair (ICC = 0.39 - 0.69).

Diagnostic ultrasound has been described as operator dependent (Beekman & Visser, 2003, 2004; Chiou et al., 2003; Martinoli et al., 2000; Peer et al., 2002) which may account for the fair reliability result. Error can occur during placement of the digital markers. It is therefore important for the sonographer to be consistent with the placement of the digital markers and callipers between trials. Blinding of the sonographer from the measurements themselves can help eliminate any measurement bias.

The reliability of longitudinal nerve movement was considered excellent at the PMT (ICC = 0.75). At the PC however, reliability analysis was performed in only three subjects. In the remaining twenty-four subjects, it was not possible to obtain sequences of longitudinal nerve movement, since the nerve moved beyond the field of the ultrasound image during the neural mobilisation exercise, i.e. the nerve was no longer in line with the transducer. Interestingly, a similar movement out of the image plane was not seen at the PMT. The observed movement of the sciatic nerve out of the image plane during measurement of longitudinal sliding at the PC, which is also consistent with an increase in transverse movement at the PC compared to the PMT, may indicate a region of high compliance behind the knee (i.e. a wavy nerve course). In the upper limb there are regions of high compliance across major joints in both the median and ulnar nerve that allow for large changes in their bed length during joint rotations (Dilley et al., 2003; Dilley et al., 2007). Through the shoulder region for example, both the median and ulnar nerves follow a wavy course, which accommodates an increase in nerve bed length during shoulder abduction. The presence of a high compliant region behind the knee is consistent with unloading of the sciatic nerve with the knee in a

flexed position (i.e. the knee was fixed in 50 degrees of flexion during the neural mobilisation).

In the present study, movement of the sciatic nerve was generated with two simultaneous movements, namely ankle plantarflexion-dorsiflexion and cervical flexion-extension. The results demonstrated sciatic nerve movement in different directional patterns depending upon the site and location (superior movement referring to superficial nerve movement towards the skin and inferior movement referring to deep nerve movement towards the femur). At the PMT (i.e. the most proximal site), distal longitudinal nerve movement was coupled with superior-medial transverse movement in 78% of trials, superior-lateral transverse movement in 9% of trials, inferior-medial transverse movement in 11% of trials and inferior-lateral transverse movement in 2% of trials (Figure 11). This is in contrast to the trials recorded at the PC which showed 100% movement of the sciatic/tibial nerve distal longitudinal movement coupled with superior-medial transverse movement (Figure 12). This finding could be explained by the differing mechanical interface at each location. At the PC, within the popliteal fossa, there is much more relative space for the nerve to more freely move compared to the tighter mechanical interface afforded by the hamstring musculature at the PMT.

4.6.1 Limitations of the study.

This study utilised an ultrasound method which enabled measurement from two-dimensional (2D) images. This method does not allow analysis of simultaneous movement within multiple planes. This poses a limitation not only of this study, but of all studies using 2D imaging which purport to accurately measure true and pure longitudinal nerve movement using diagnostic ultrasound. It has been suggested that the use of three (3D) and four-dimensional (4D) diagnostic ultrasound scanner may

present an opportunity to measure real-time soft-tissue movement in multiple planes thereby giving a more accurate representation of actual movement (Deng et al., 2000).

4.7 CONCLUSION

The study concluded that using diagnostic ultrasound assessment and frame-by-frame cross-correlation analysis to quantify sciatic nerve movement, it is possible to provide excellent reliability for measurement of longitudinal sciatic nerve movement during neural mobilisation. The reliability of the transverse movement of the sciatic nerve was fair irrespective of location or direction.

REFERENCES

References for this paper can be found in the Reference list at the back of the published paper (see Appendix 10). The references for this paper have also been included in the full reference list of this thesis.

Chapter Five. The influence of increased nerve tension on sciatic nerve excursion during a side-lying neural mobilisation exercise - a reliability study

5.1 PRELUDE

For the initial reliability study of this doctoral research a standardised, upright sitting posture was utilised for the neural mobilisation exercise. The hip and knee joints were held at 90° and 50° flexion respectively. In all participants the right leg was imaged. Following this study, excellent reliability of measuring longitudinal sciatic nerve movement at the posterior mid-thigh during simultaneous cervical extension and ankle dorsiflexion (neural mobilisation), using high-resolution ultrasound and frame-by-frame cross-correlation analysis, was concluded.

Subsequent to this initial study, consideration was given to the use of a side-lying neural mobilisation for analysis of sciatic nerve excursion. Neural mobilisation techniques undertaken in side-lying have been previously suggested for patients with neurodynamic dysfunction (Cleland et al., 2004; Shacklock, 1995b, 2005a). Potentially side-lying would offer another advantageous participant position with which to gain easy access to the PMT for sciatic nerve scanning. Furthermore, the addition of nerve tension was used during the neural mobilisation. This was done in order to see whether increased nerve tension would influence sciatic nerve excursion.

The objective of this study was twofold. Firstly, to examine the influence of added nerve tension upon sciatic nerve excursion, during a neural mobilisation exercise. Secondly, to build on the initial reliability study (Chapter Four) to establish whether similar levels of longitudinal sciatic movement were seen with equivalent levels of reliability when using a side-lying neural mobilisation compared to a seated

mobilisation. Furthermore, added neural tension was used in order to see whether additional nerve tension would reduce sciatic nerve excursion during the mobilisation.

5.2 ABSTRACT

Background: ultrasound imaging has been successfully used to measure the amount of peripheral nerve movement. This study utilised USI to assess changes in the amount of longitudinal sciatic nerve movement, when exposed to increased load, during a side-lying neural mobilisation, in healthy asymptomatic participants. The reliability of using USI to measure longitudinal sciatic nerve movement, in the modified slump position, was also assessed.

Methods: Thirteen participants (five males and eight females) were involved and were aged between 20 and 44 years. Longitudinal sciatic nerve movement was recorded and measured using USI. The participants were placed in side-lying with their hip and knee flexed to 90°. Longitudinal sciatic nerve movement was measured at three positions of progressive neural tension (i.e. with greater knee extension and level of stretch measured by a 10-point numeric rating scale (NRS) set at 0/10, 2/10 and 4/10 stretch). Sciatic nerve movement was induced with passive ankle movement from full plantarflexion to full dorsiflexion coupled with simultaneous active cervical flexion to extension. The reliability of measuring longitudinal sciatic nerve movement at each of the three positions was also calculated.

Results: There were statistically significant differences ($P<0.005$) seen in the mean amount of longitudinal sciatic nerve movement between positions NRS 0/10 (0.59mm) and NRS 2/10 (0.99mm) and also between positions NRS 2/10 (0.99mm) and NRS 4/10 (0.52mm). The reliability (ICC (95% CI); SEM; MDC) of measuring

longitudinal sciatic nerve movement was for NRS 0/10 0.95 (0.88–0.99; 0.10mm; 0.28mm), for NRS 2/10 0.89 (0.70–0.97; 0.21mm; 0.59) and for NRS 4/10 0.94 (0.83–0.98; 0.09; 0.24mm).

Discussion: The amount of sciatic nerve excursion, during a slide-lying neural mobilisation exercise, varied depending on the amount of knee extension and therefore sciatic nerve tension in the exercise position. The amount of sciatic nerve excursion was less than seen in the previous study which utilised a seated exercise. Differences in nerve mechanics, which may have been evident given the two different positions, likely influenced the level of nerve excursion seen. However, the reliability of measuring sciatic nerve excursion was excellent which is in line with the previous study.

5.3 INTRODUCTION

Neurodynamic theories suggest that nerve movement will diminish as greater amounts of tension and load are placed upon the nerve tract. As the resting slack of a peripheral nerve is taken up, eventually there will be relatively less nerve excursion and greater elongation (Charnley, 1951; Dilley et al., 2007; Kwan et al., 1992; McLellan & Swash, 1976; Shacklock, 1995b, 2005a; Topp & Boyd, 2006). In order to maximise nerve excursion during neural mobilisation exercises, it is important to understand how much nerve tension can be placed upon a nerve tract before the sliding capacity of that nerve is compromised.

Human cadaveric experiments have shown that during a straight-leg raise (SLR), excursion of the sciatic nerve initially started after the first 5° of hip flexion (Goddard & Reid, 1965) or following 15-30º of hip flexion (Breig & Troup, 1979b; Charnley, 1951; Fahrni, 1966; Inman & Saunders, 1941). As the SLR continued, progressively less

actual sliding occurred, so that by greater than 70° of hip flexion, sliding diminished and elongation occurred (Charnley, 1951; Gajdosik et al., 1985; Gifford, 1998; Goddard & Reid, 1965; Shacklock, 2005a).

An *in-vivo* analysis of longitudinal median nerve excursion has also examined the effect of additional neural tension upon nerve movement. Less median nerve excursion was seen during wrist extension with the elbow joint positioned in extension (and therefore pre-loaded) compared to flexion. Likewise, median nerve excursion was less during elbow extension when the wrist was positioned in neutral compared to 45° flexion. Essentially the more tension that the median nerve was exposed to, the less nerve excursion was seen (Dilley et al., 2003). This same phenomenon was witnessed by examination of median nerve excursion in the forearm, with nerve movement induced by wrist extension. Here, significant median nerve excursion was not witnessed until the slack of the median nerve was taken up by extending the elbow (Dilley et al., 2003).

Clinically the influence of additional neural tension can be seen during neurodynamic testing where joint ROM decreases as tension is progressively added to the PNS. For example, studies which have examined knee ROM during a slump test have concluded that significantly less knee extension occurred with the addition of cervical flexion (Fidel et al., 1996; Herrington et al., 2008; Johnson & Chiarello, 1997; Tucker et al., 2007). The explanation given for the reduction in knee extension was that cervical flexion imposed additional tension upon the neuromeningeal structures at the spinal cord and nerve roots leading to a reciprocal increase in tension further down to the sciatic nerve tract (Fidel et al., 1996; Herrington et al., 2008; Johnson & Chiarello, 1997; Tucker et al., 2007; Yeung et al., 1997).

There were two aims of this study. The first aim was to quantify the amount of longitudinal sciatic nerve movement, using USI at the PMT, during a side-lying neural mobilisation exercise with the lower limb positioned with different amounts of nerve tension. It was hypothesised that nerve excursion would be reduced as tension increased upon the sciatic nerve.

The second aim of this study was to further assess the reliability of using USI to measure longitudinal sciatic nerve movement, during a side-lying neural mobilisation exercise. It was hypothesised that the reliability of measurement of longitudinal sciatic nerve movement would be similar to that seen from a previous study which utilised a seated neural mobilisation exercise (see Chapter Four).

5.4 METHODS

5.4.1 Participants.

Fourteen participants (six males and eight females) volunteered for this study and met the inclusion and exclusion criteria. The inclusion and exclusion criteria were healthy individuals between the ages of 18-50 who did not have a history of significant/major trauma or surgery to the lumbar, hip, buttock (gluteal) or hamstring (posterior thigh) regions; symptoms consistent with sciatic nerve impairment (i.e. paraesthesias, weakness, etc.); or a positive slump test, as described by Butler (2000). All participants were asked to read an information sheet regarding the study and then informed, written consent was obtained. Ethics approval was sought and approved by AUTEC (Auckland University of Technology Ethics Committee) (see Appendix 3).

5.4.2 Procedure.

The participants were positioned in side-lying on a plinth. Their back and head were aligned against a wall to ensure the spine was in a neutral position. The hips and knees were positioned in 90° of flexion and these angles were measured using an electrogoniometer. A sliding board was placed on a table adjacent to the plinth and the participants were directed to place their left leg on the sliding board. An inflatable cuff was used to adjust the height of the thigh to ensure the hip joint was in a neutral position in the transverse plane, as measured using an inclinometer (Figure 15). The left leg was imaged in all participants. The sciatic nerve was imaged at a point along the posterior mid-thigh (PMT), halfway between the gluteal and popliteal creases.
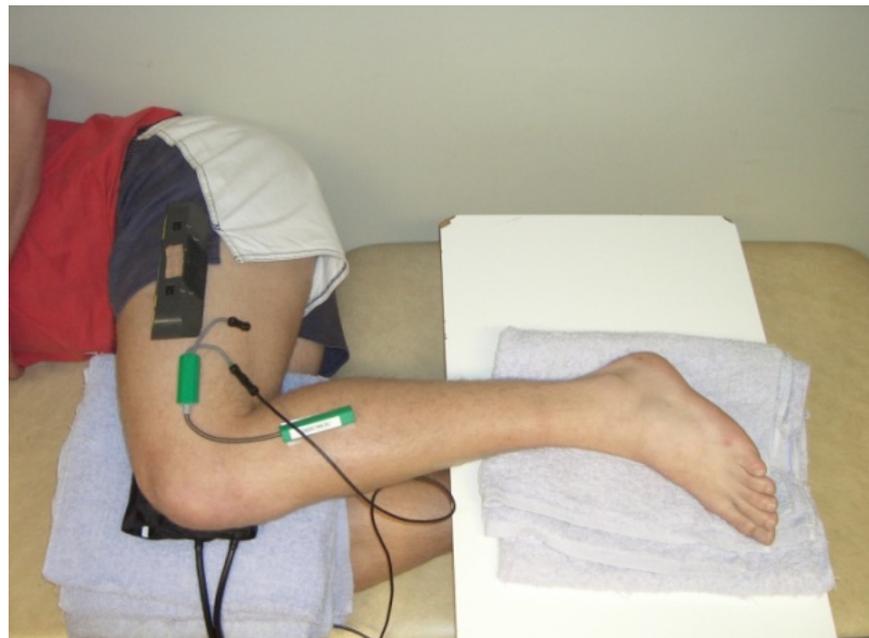
Figure 15. Participant set-up for side-lying neural mobilisation

The first ultrasound measurements were taken with the knee placed in 90° of flexion. At this position participants were asked whether they could rate the amount of stretch they perceived in their hamstring region on a numeric rating scale (NRS). A

score of 0 represented "no stretch". A score of 10 represented "the maximum tolerable stretch". Whilst in this first position (NRS 0/10 position), when asked, all participants reported "no stretch".

Over a three second period, sciatic nerve movement was initiated by passively moving the ankle from a position of maximal plantarflexion to a position of maximal dorsiflexion along with simultaneous active cervical flexion to extension. Three ultrasound recordings of longitudinal sciatic nerve excursion at the PMT were taken for three separate movements.

The participants were then asked to extend their knee to a position where a stretch in the hamstring occurred that they rated as 2 out of 10 on the NRS (NRS 2/10 Position). Once again three ultrasound recordings were taken for three separate movements using the same test movement as that detailed above.

Following measurement in this position the participants were asked to extend their knee to a position where the stretch on the hamstring was rated as 4 out of 10 on the NRS (NRS 4/10 Position). Finally three ultrasound recordings were taken for three separate movements using the same test movement as that detailed above. The sonographer was blinded to all ultrasound measurements taken.

5.4.3 Ultrasound imaging and analysis.

The ultrasound recordings were captured by the same sonographer. B-mode USI was performed using a Philips HD11 (Philips Medical Systems Co., Eindhoven, The Netherlands) ultrasound machine with a 5 to 12 MHz, 55mm linear array transducer. The sciatic nerve was imaged at the PMT and an ultrasound cine-loop was used to

record the movement in the longitudinal plane. The images were recorded using a video loop of three seconds in duration at 40 frames per second.

The video sequences were converted to a digital format (bitmaps). Each video sequence was then analysed off-line using a method of frame-by-frame cross-correlation analysis that was developed in Matlab (Mathworks, USA) by Dilley et al. (2001). This method employs a cross-correlation algorithm to determine relative movement between successive frames in a sequence of ultrasound images (Dilley et al., 2001). During the analysis, the program compares the gray scale values of speckle features from the regions of interest (ROI's) within the nerve between adjacent frames of the image sequence. In the compared frame, the coordinates of the ROI are offset along the horizontal and vertical image planes a pixel at a time within a predetermined range. A correlation coefficient is calculated for each individual pixel shift. The peak of a quadratic equation, fitted to the maximum three correlation coefficients, allows determination of sub-pixel accuracy. In doing so this further refines the algorithm by more accurately assessing the maximum cross-correlation value. This peak is equivalent to the pixel shift/movement between adjacent frames. Therefore this algorithm establishes that the degree of pixel shift that has the highest associated correlation coefficient corresponds to and represents the relative movement which is measured (Dilley et al., 2001).

Pixel shift measurements for the nerve were offset against (subtracted from) pixel shifts measurements within the same ultrasound field, from stationary structures (i.e. subcutaneous layers, bone, etc.). This method allows for any slight movement of the ultrasound transducer to be eliminated from the analysis. This method has proved to be a highly reliable method of assessment of nerve motion (Coppieters et al., 2009; Dilley et al., 2001).

5.4.4 Statistical analysis.

In regard to the first research aim (changes of nerve excursion in response to increased nerve tension), mean longitudinal sciatic nerve excursion was calculated for each of the test positions (NRS 0/10, NRS 2/10 and NRS 4/10). T-tests, with alpha level set at 0.05, were then used to compare mean values of excursion at each position.

In regard to the second research aim (reliability of measurement), intraclass correlation coefficients (ICC) were calculated for the test-retest measurements across the three successive trials in each test position. The standard error of measurement (SEM) and minimal detectable change (MDC) were calculated for each of the three testing positions. All statistics were calculated using SPSS (version 14) statistical analysis software.

5.5 RESULTS

Fourteen participants met the inclusion and exclusion criteria. The data from one participant was eventually withdrawn as there was poor visualisation of the sciatic nerve from the ultrasound footage. Of the thirteen remaining participants, there were eight females and five males. The average age of the participants was 26.08 years (range: 20-44 years).

The amount of longitudinal sciatic nerve movement was (mean±SD) 0.59mm ± 0.47mm for NRS 0/10, 0.99mm ± 0.65mm for NRS 2/10 and 0.52mm ± 0.36mm for NRS 4/10 positions respectively.

There were statistically significant differences ($P<0.005$) seen in the mean amount of longitudinal sciatic nerve movement between positions NRS 0/10 (0.59mm)

and NRS 2/10 (0.99mm) and also between positions NRS 2/10 (0.99mm) and NRS 4/10 (0.52mm).

The reliability (ICC (95% CI); SEM; MDC) of measuring longitudinal sciatic nerve movement was for NRS 0/10 0.95 (0.88–0.99; 0.10mm; 0.28mm), for NRS 2/10 0.89 (0.70–0.97; 0.21mm; 0.59) and for NRS 4/10 0.94 (0.83–0.98; 0.09; 0.24mm).

5.6 DISCUSSION

This study sought to establish whether the amount of longitudinal sciatic nerve excursion during a side-lying neural mobilisation exercise differed when additional tension was added to the sciatic nerve. Tension to the sciatic nerve tract, as determined by an increased subjective reporting of posterior thigh stretch, was added prior to performing the neural mobilisation exercise by progressively extending the knee, whilst in the side-lying position. The findings of this study showed that when no stretch was felt (NRS 0/10) there was significantly less sciatic nerve excursion compared to when stretch was rated at 2/10 on the NRS (0.59mm compared to 99mm respectively). However, from increasing the posterior thigh stretch from 2/10 to 4/10 on the NRS there was a significant reduction in sciatic nerve excursion (0.99mm compared to 0.52mm respectively).

At the NRS 0/10 no stretch was reported by any of the participants. That being the case, it was assumed that very little (if any) tension was placed upon the sciatic nerve. When passive ankle dorsiflexion was performed there was a small amount of sciatic nerve excursion recorded (0.59mm). This value suggested a small amount of nerve movement occurred potentially as the slack of the resting slack of the nerve was taken up.

To reach the NRS 2/10 position, the knee was passively extended which would have caused increased tension on the sciatic nerve, along with other posterior thigh structures. The increased nerve excursion seen at the NRS 2/10 position may be explained due to nerve slack being reduced and increased nerve sliding occurring.

The third position moved the knee further into extension resulting in a greater stretch being applied to the sciatic nerve (4/10 subjective feeling of stretch on a NRS). With the additional nerve stretch, sciatic nerve excursion decreased from 0.99mm at the NRS 2/10 position to 0.52mm at the NRS 4/10 position. This decrease in nerve excursion may be explained as less sliding is occurring due to the presence of increased nerve tension.

Of note is the significant reduction in sciatic nerve excursion seen from this study compared to the initial reliability study (Chapter Four). The range of all data for longitudinal sciatic nerve excursion, recorded at the PMT during the neural mobilisation, in this side-lying study was 0.02mm–2.43mm (mean 0.70mm) compared to the sitting based study (sitting) 0.45mm-8.61mm (mean 3.47mm). There are several reasons why a large difference in sciatic nerve excursion was recorded between the two positions (sitting versus side-lying) was seen.

Firstly, the knee position varied between studies which would have influenced the amount of pre-load upon the sciatic nerve tract and therefore the amount of nerve excursion. For the sitting based study (Chapter Four) the knee was held constant at 50° flexion. For the current side-lying study (Chapter Five) the mean knee position for NRS 2/10 position was 45.92° flexion and for the NRS 4/10 position 34.85° (0° equals terminal knee extension). The mean sciatic nerve excursion at the NRS 2/10 position (the closest knee position to the 50° flexion used in the reliability study) was 0.99mm, once again significantly less than the 3.47mm in the reliability study.

Secondly, the influence of gravity may have had a significant effect. The influence of gravity upon the spinal cord, lumbo-sacral nerve roots and sciatic nerve tract is different between a side-lying and a sitting position. Several studies, which have examined the morphology and location of the spinal cord and cauda equina for lumbar epidural and puncture procedures, have recorded that the position of the spinal cord and cauda equina shift depending on the position a person adopts. This shift is gravity dependent, for example the spinal cord and cauda equina has been shown to migrate anteriorly (approximately 6.3mm at the conus medullaris) (Ranger, Irwin, Bunbury, & Peutrell, 2008) and toward the ipsilateral side that the person was lying on (approximately between 1.6 - 3.4mm at the lumbar nerve roots) (Ranger et al., 2008; Takiguchi, Yamaguchi, Hashizume, & Kitajima, 2004a; Takiguchi, Yamaguchi, Okuda, & Kitajima, 2004b; Takiguchi, Yamaguchi, Usui, Kitajima, & Matsuno, 2006; Takiguchi, Yamaguchi, Tezuka, & Kitajima, 2009) which was exaggerated (i.e. greater shift to the lower side) when the knees and hips were flexed (up to 6.1mm at the lumbar nerve roots) (Takiguchi et al., 2004a; Takiguchi et al., 2009).

The potential exists that, in a side-lying position because of the documented gravity-dependent shift in the neural tissues, the tension that is imposed on the lumbo-sacral nerve roots and sciatic nerve tract was significantly different to that imposed in sitting which subsequently led to the reduction in sciatic nerve excursion seen during the side-lying study.

The second aim of this study was to test the reliability of measuring longitudinal sciatic nerve excursion, using USI, during a neural mobilisation exercise performed in side-lying. An ICC of below 0.40 represents poor reliability, 0.40 - 0.75 represents fair reliability and above 0.75 represents excellent reliability (Fleiss, 1986). The reliability of the nerve movement at all three positions was considered excellent (NRS 0/10

Position 0.95, NRS 2/10 Position 0.89, NRS 4/10 Position 0.94). The 95% CI's however were reasonably close in respect to their spread (between 0.70-0.99 over the three positions). These ICC values indicate a higher level of reliability of measuring sciatic nerve excursion compared to the seated neural mobilisation (ICC 0.75) (Chapter Four). However, with the mean values of excursion being substantially smaller, this may also have contributed to the high levels of reliability.

5.7 CONCLUSION

In agreement with current neurodynamic theories, this study suggests that the addition of increased nerve tension, once the resting slack of the sciatic nerve was taken up, resulted in decreased nerve excursion during a neural mobilisation exercise performed in side-lying. The reliability of measuring longitudinal sciatic nerve excursion, with USI, during a side-lying neural mobilisation exercise was excellent.

Compared to the side-lying position, the sitting position afforded a greater potential for sciatic nerve excursion. Furthermore, as seated neural mobilisation exercises, for the sciatic nerve tract, are more commonly used in clinical practice it was decided to return to using a sitting position for future studies as part of this research.

REFERENCES

The references for this paper have been included in the full reference list of this thesis.

Chapter Six. Comparison of different neural mobilisation exercises upon longitudinal sciatic nerve movement: an *in-vivo* study utilising ultrasound imaging

6.1 PRELUDE

The previous papers concluded that the intra-rater reliability of USI and frame-by-frame cross-correlation analysis to quantify *in-vivo* longitudinal sciatic nerve excursion, during neural mobilisation exercises, was excellent. Therefore this method provides a suitable tool to assess the amount of sciatic nerve excursion that occurs during different types of neural mobilisation exercises.

Different neural mobilisation exercises have been proposed to have different effects. Understanding these effects will be crucial for appropriate neural mobilisation design and prescription. In regard to nerve excursion, sliders have been seen to result in greater nerve excursion compared to tensioners (Coppieters & Alshami, 2007; Coppieters & Butler, 2008; Coppieters et al., 2009). At present, this has only been examined *in-vivo* within the upper limb (Coppieters et al., 2009).

This third aim of this thesis was to assess whether the amount of longitudinal sciatic nerve excursion differed across different types of neural mobilisation exercises. Accordingly a controlled laboratory study using a single-group, within-subject comparisons was utilised to assess the amount of longitudinal sciatic nerve excursion that occurred with different types of slump-sitting neural mobilisation exercises (two-ended slider, one-ended slider and a tensioner). Previous research in the upper limb has concluded that different amounts of median nerve excursion occurred during different neural mobilisation exercises (Coppieters et al., 2009). This study is the first to

examine this situation in the lower limb. A paper from this chapter has been submitted for publication in the "Journal of Orthopaedic and Sports Physical Therapy".

6.2 ABSTRACT

Study Design: A controlled laboratory study using a single-group, within-subject comparisons

Objectives: An *in-vivo* study to determine whether different types of neural mobilisation exercises are associated with differing amounts of longitudinal sciatic nerve excursion

Background: Recent research in the upper limb, of healthy participants, has concluded that nerve excursion differs significantly between different types of neural mobilisation exercises. This has not been examined in the lower limb. It is important to initially examine the influence of neural mobilisation upon peripheral nerve excursion in healthy people in order to appreciate peripheral nerve excursion in conditions where nerve excursion may be compromised.

Methods: High-resolution ultrasound was used to assess sciatic nerve excursion at the posterior mid-thigh. Four different neural mobilisation exercises were utilised in thirty-one healthy participants. These neural mobilisation exercises used combinations of knee extension and cervical flexion and extension. Frame-by-frame cross-correlation analysis was used to calculate nerve excursion. A repeated-measures analysis of variance and isolated means comparisons were used to analyse these data.

Results: Different neural mobilisation exercises induced significantly different amounts of sciatic nerve excursion ($P<0.001$). The slider was associated with the largest sciatic nerve excursion (3.2±2.0mm) and was significantly greater ($P<0.02$) than

seen with a single-joint mobilisation (2.6±1.4mm; *P*<0.02) and a tensioner (2.6±1.5mm).

Conclusion: These findings support previous research which has examined median nerve excursion associated with different neural mobilisation exercises. Appreciation of such excursion provides support for theoretical perspectives of nerve motion being generalisable to the lower limb.

Keywords: *diagnostic ultrasound, nerve biomechanics, nerve sliding*

6.3 INTRODUCTION

The use and description of neural mobilisation exercises to influence the mechanical properties of peripheral nerves gained popularity through the late 1970's through to the mid 1980's. However the underlying mechanisms associated with clinical improvements following neural mobilisation remains unclear (Brown et al., 2011). There are many theories which have been postulated including physiological effects [i.e. removal of intraneural oedema (Brown et al., 2011; Butler, 2000; Coppieters et al., 2004; Ellis & Hing, 2008; Shacklock, 2005a)], central effects [i.e. reduction of dorsal horn and supraspinal sensitisation (Butler, 2000; Coppieters & Butler, 2008)] and mechanical effects [i.e. enhanced nerve excursion (Butler, 2000; Coppieters & Alshami, 2007; Coppieters & Butler, 2008; Coppieters et al., 2009; Ellis & Hing, 2008; Méndez-Sánchez et al., 2010; Shacklock, 2005a)].

Neural mobilisation exercises have been developed from neurodynamic tests (Butler & Gifford, 1989b; Coppieters et al., 2009; Maitland, 1985; Shacklock, 1995b). There is evidence to suggest that neurodynamic tests encourage peripheral nerve movement through elongation of the nerve bed (Byl et al., 2002; Coppieters et al., 2006;

Dilley et al., 2003; Wilgis & Murphy, 1986; Wright et al., 2005). It is from this body of evidence that neural mobilisation exercises have evolved in an attempt to therapeutically maximise movement in conditions that nerve movement and elongation is perceived to be compromised.

Until recently, concepts regarding the mechanical influence of neural mobilisation upon the peripheral nervous system were grounded in theory rather than concrete evidence. Subsequently, it is likely that many highlighted RCTs (Ellis & Hing, 2008), which have examined neural mobilisation, chose exercises on a theoretical and pragmatic basis rather than specifically designing exercises to match clinical conditions. Several studies which have examined neural mobilisation have stated specifically that the exercises utilised were chosen based solely on those used in previous research (Akalin et al., 2002; Bardak et al., 2009; Baysal et al., 2006; Heebner & Roddey, 2008; Pinar et al., 2005). Now that a growing body of evidence is emerging regarding the mechanical effects that neural mobilisation exercises have upon peripheral nerves, it is imperative to design exercises to specifically suit certain conditions based on an understanding that specific mechanical features can be enhanced. However, before this can be achieved, more attention must be given to understanding the influence of neural mobilisation exercises upon normal nerve excursion.

Recent studies have examined the influence of neural mobilisation upon nerve mechanics in cadavers (Coppieters & Alshami, 2007; Coppieters & Butler, 2008) and subsequently *in-vivo* research has been undertaken (Coppieters et al., 2009; Echigo et al., 2008; Ellis, Hing, Dilley, & McNair, 2008). Coppieters et al. (Coppieters et al., 2009) examined the difference in median nerve excursion between different types of nerve-gliding exercises (including sliders and tensioners). Sliders utilise combinations of joint movements to encourage peripheral nerve sliding/excursion by increasing

elongation at one end of the nerve bed, therefore increasing tension in the nerve, whilst simultaneously releasing tension from a distant aspect of the nerve bed (Beneciuk et al., 2009; Butler, 2000; Coppieters & Alshami, 2007; Coppieters & Butler, 2008; Coppieters et al., 2009; Herrington, 2006; Shacklock, 2005a). In doing so, excursion is promoted without significant increase in nerve tension that is associated with elongation or tensioning exercises (Coppieters & Alshami, 2007; Coppieters & Butler, 2008). In contrast, tensioners utilise combinations of joint movements that elongate the nerve bed from both ends in an attempt to stretch the neural connective tissues (Butler, 2000; Coppieters & Butler, 2008; Coppieters et al., 2009; Herrington, 2006; Shacklock, 2005a).

The conclusion has been that, of the nerve-gliding exercises that were assessed, sliders produce greater amounts of median nerve excursion compared to tensioners (Coppieters & Alshami, 2007; Coppieters & Butler, 2008; Coppieters et al., 2009). It has also been shown that there is a difference between certain types of neural mobilisation exercises, i.e. significantly less nerve excursion induced from nerve-gliding exercises initiated at one point along the nerve bed versus sliders (Coppieters et al., 2009).

Neural mobilisation exercises, derived from neurodynamic tests such as the slump test or straight-leg raise test, for lumbar spine and lower limb clinical conditions have been advocated in clinical texts (Butler, 2000, 2005; Maitland, 1985; Shacklock, 2005a) and following clinical trials (Bertolini et al., 2009; Cleland et al., 2007; Herrington, 2006; Kornberg & Lew, 1989; Schafer, Hall, Muller, & Briffa, 2011; Webright, Randolph, & Perrin, 1997). However, to the authors' knowledge, no previous research has been published which has examined *in-vivo* measurement of sciatic nerve excursion in normal healthy participants during different types of neural

mobilisation exercises. Such work would support theoretical perspectives that to date have only received experimental support from studies in the upper limb. The generalisability of such theory would be enhanced if it could be shown that similar trends exist in the lower limb where anatomical structures and motion are different.

The aim of this study was to examine longitudinal sciatic nerve excursion at the posterior mid-thigh (PMT), using high-resolution ultrasound (US), during slump-sitting neural mobilisation exercises. This research was conducted with healthy participants in order to assess normal nerve excursion. In line with previous studies (Coppieters & Alshami, 2007; Coppieters & Butler, 2008; Coppieters et al., 2009) it was hypothesised that sliders would induce greater longitudinal sciatic nerve excursion compared to tensioners and that sliders will induce greater longitudinal sciatic nerve excursion compared to nerve-gliding exercises utilising single joint movements.

6.4 METHODS

6.4.1 Participants.

Thirty-one healthy participants (22 females, 9 males; range 21-61 years; mean±SD age 29±9 years, height 170.5cm±7.5, weight 68.6kg±13, BMI 23.4±3) were included in this study. Participants met the inclusion criteria if they were healthy individuals over the age of 18 years and did not have symptoms suggestive of sciatic nerve dysfunction.

Participants were excluded if they had a history of significant/major trauma or surgery to the lumbar, hip, buttock (gluteal) or hamstring (posterior thigh) regions, symptoms consistent with sciatic nerve impairment (i.e. paraesthesias, weakness, etc.), or a positive slump test (a test which determines mechanosensitivity of the sciatic nerve

and its associated branches) as described by Butler (2000). Participants were also excluded if they had a neurological condition or other disorders which might alter the function of the nervous system, for example diabetes.

Based upon a pilot study of 15 participants, a power analysis and sample size calculation was performed using G*Power 3 (Erdfelder, Faul, & Buchner, 1996; Faul, Erdfelder, Lang, & Buchner, 2007). The dependant variable used for this analysis was sciatic nerve excursion, between the different neural mobilisation exercises, with power set at 0.8 and the α=0.05, the number of participants required was 21. Following the pilot study and power analysis, a review of the procedures and methods used was conducted. From this it was deemed that the procedures were appropriate and no changes were necessary. Prior to the power analysis, participant recruitment had already found another 16 participants. Based on the conclusion that no procedural changes were to be made, the data of the 15 participants from the pilot study were pooled with the remaining 16 participants.

Participants were provided with both written and verbal information concerning the testing procedures. Informed consent was given by all participants. The study was approved by the Auckland University of Technology Ethics Committee (AUTEC) (see Appendix 8).

6.4.2 Participant set-up.

A Biodex system 3 isokinetic dynamometer (Biodex Medical, Shirley, NY, USA) was used to provide a consistent, fixed and supported sitting position and enable standardised passive joint movement to facilitate the neural mobilisation exercises. Participants were positioned on the Biodex seat and asked to adopt a slumped spinal
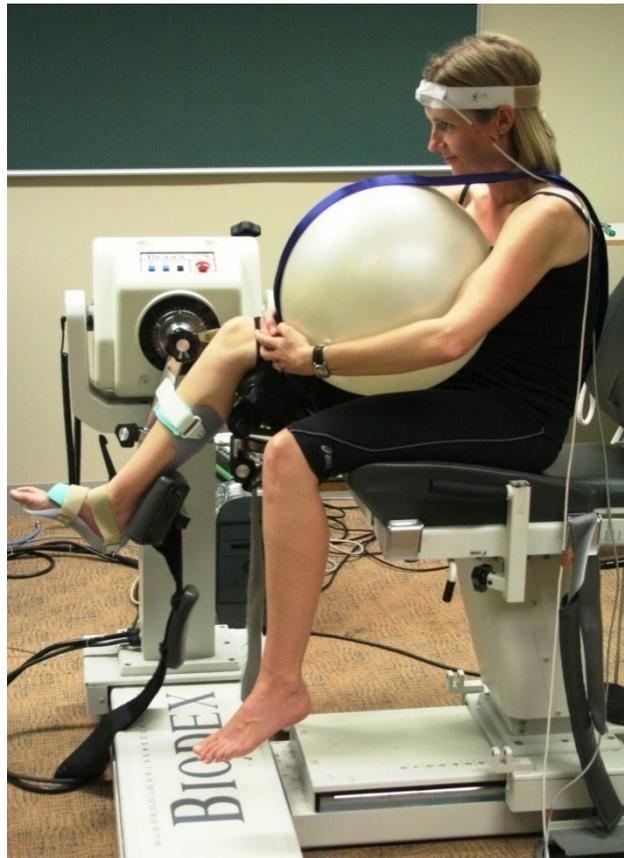
Figure 16. Participant set-up for slump-sitting neural mobilisation exercises.

position. This involved a sitting position where the spine was relaxed forwards into a

flexed position through the length of their spine. Once in the slump position, the trunk

of each participant was brought forwards until the right hip joint was at 90° flexion, as

measured by a universal goniometer. The slump position was maintained with contact

of the sternum against a 45cm diameter swiss ball which was placed on the participants

lap. A seatbelt was then utilised to maintain this position (Figure 16).

6.4.3 Fastrak electrogoniometer.

Range of movement (ROM) at the cervical spine and knee joints was measured

with a 3-Space Fastrak (Polhemus Inc., Colchester, Vermont, USA) electromagnetic

motion tracking system. The Fastrak is a device that tracks the position of up to four separate sensors, in real-time within six-degrees of freedom across three dimensions, in respect to a source unit which emits a low-intensity electromagnetic field. The position and orientation of each of the sensors (angular and linear displacement) within the electromagnetic field is recorded at a set frequency (30 samples per second when using four sensors). The Fastrak system has been shown to be accurate to within $\pm 0.2°$ when recording spinal motion (Pearcy & Hindle, 1989).

For cervical Fastrak measurements, Sensor 1 was placed at the middle of the forehead (in line with the bridge of the nose) (Amiri, Jull, & Bullock-Saxton, 2003; Dall'Alba, Sterling, Treleaven, Edwards, & Jull, 2001; Jasiewicz, Treleaven, Condie, & Jull, 2007; Sterling, Jull, Carlsson, & Crommert, 2002; Trott, Pearcy, Ruston, Fulton, & Brien, 1996) using an adjustable elastic headband. Sensor 2 was placed over the spinous process of C7, and secured with double sided tape and tape over the top of the sensor. For knee Fastrak measurements both sensors were secured (using double sided tape) on the lateral aspect of the leg, Sensor 1 100mm above the lateral joint line and Sensor 2 100mm below the joint line (Bullock-Saxton, Wong, & Hogan, 2001).

In order to avoid potential interference from other metallic objects within the electromagnetic field, the electromagnetic source unit was secured to a wooden pole and elevated from the ground as recommended by previous studies utilising the Fastrak system (Bullock-Saxton et al., 2001; Hemmerich, Brown, Smith, Marthandam, & Wyss, 2006). The supporting pole was placed far enough in front of the participant and other metal equipment to ensure no interference. Prior calibration involved placing all four sensors, in pairs, against a universal goniometer which was moved through a set angle. No interference of the Fastrak system was evident.

The Fastrak was linked to a computer which recorded the signals being transmitted from the sensors. LabVIEW 2009 (Version 9.0f2, National Instruments, Austin, TX, USA) computer software was utilised to allow real-time visualisation and recording of the motion trace. The joint angle data, as recorded from the cervical spine and knee were then synchronised off-line to the recorded US sequences.

6.4.4 Diagnostic US parameters and imaging.

Excursion of the sciatic nerve was assessed at the level of the PMT (half-way between the gluteal crease and popliteal crease). Ellis et al. (2008) previously concluded high levels of reliability (two-way mixed, intraclass correlation coefficient (ICC) of 0.753) for measurement of longitudinal sciatic nerve excursion at this location. Initial transverse imaging at the PMT allowed localisation of the sciatic nerve. Once identified, the US transducer was rotated into the longitudinal plane. This method of peripheral nerve location is recommended (Coppieters et al., 2009; Echigo et al., 2008). A sonographer with five years experience performed all US scans. During the US sequence selection and cross-correlation analysis the researcher was blinded to the participant (including their relevant demographic data), the recording session and the neural mobilisation exercise that was tested.

B-mode real time US scanning was performed using a Philips iU22 (Philips Medical Systems Company, Eindhoven, The Netherlands) US machine with a 12-5 MHz, 50mm, linear array transducer. An US sequence of the nerve in a longitudinal plane was recorded for each exercise trial. The video sequence was captured over a three second period at a capture rate of 30 frames per second.

6.4.5 Frame-by-frame cross-correlation algorithm and calculation software.

Each video sequence was converted to a digital format (bitmaps). The image size for each of the frames was 800x600 pixels. ImageJ (Version 1.42, National Institute of Health, Maryland, USA) digital image analysis software was used to calculate the image resolution and also the scale conversion for pixels to millimetres. Image resolution varied between 7.3 − 10.4 pixels/millimetre depending on the depth of US penetration required to capture the sciatic nerve.

Each video sequence was then analysed off-line using a method of frame-by-frame cross-correlation analysis that was developed in Matlab (Mathworks, USA) by Dilley et al. (2001). This method employs a cross-correlation algorithm to determine relative movement between successive frames in a sequence of US images (Dilley et al., 2001). During the analysis, the program compares the gray scale values of speckle features from the regions of interest (ROI's) within the nerve between adjacent frames of the image sequence. In the compared frame, the coordinates of the ROI are offset along the horizontal and vertical image planes a pixel at a time within a predetermined range. A correlation coefficient is calculated for each individual pixel shift.

The peak of a quadratic equation, fitted to the maximum three correlation coefficients, allows determination of sub-pixel accuracy. In doing so this further refines the algorithm by more accurately assessing the maximum cross-correlation value. This peak is equivalent to the pixel shift/movement between adjacent frames. Therefore this algorithm establishes that the degree of pixel shift that has the highest associated correlation coefficient corresponds to and represents the relative movement which is measured (Dilley et al., 2001).

Pixel shift measurements for the nerve were offset against (subtracted from) pixel shifts measurements within the same US field, from stationary structures (i.e.

subcutaneous layers, bone, etc.). This method allows for any slight movement of the US transducer to be eliminated from the analysis. This method has proved to be a highly reliable method of assessment of nerve motion (Coppieters et al., 2009; Dilley et al., 2001; Ellis et al., 2008).

6.4.6 US video selection criteria.

Each US video sequence was reviewed several times. To be selected for analysis, the video sequence must have had clear pixilation and clear identification of the sciatic nerve throughout the three second duration. The sciatic nerve must have stayed within the longitudinal plane of the US transducer, and therefore stayed within the US image. Of the video sequences that met these criteria, two were randomly chosen for each of the eight neural mobilisations per participant for cross-correlation analysis.

During the US sequence selection and cross-correlation analysis the researcher was blinded to the participant (including their relevant demographic data), the recording session and the neural mobilisation exercise that was tested.

6.4.7 Neural mobilisation exercises.

1A. Slider mobilisation: Simultaneous passive knee extension (from 80º flexion to 20° flexion - loading of the sciatic nerve caudally via the tibial nerve) with active cervical extension (from full comfortable cervical flexion to full comfortable cervical extension - unloading of nervous system cranially).

1B. Single-joint mobilisation: Passive knee extension (from 80º flexion to 20° flexion - loading of the sciatic nerve caudally via the tibial nerve). Each participant was instructed to look straight ahead in order to maintain their cervical spine in a neutral position.

1C. Single-joint mobilisation: active cervical flexion (from full comfortable cervical extension to full comfortable cervical flexion - loading of nervous system cranially). The knee was held stationary at 80° of knee flexion.

1D. Tensioner mobilisation: Simultaneous passive knee extension (from 80º flexion to 20° flexion - loading of the sciatic nerve caudally via the tibial nerve) with active cervical flexion (from full comfortable cervical extension to full comfortable cervical flexion - loading of nervous system cranially).
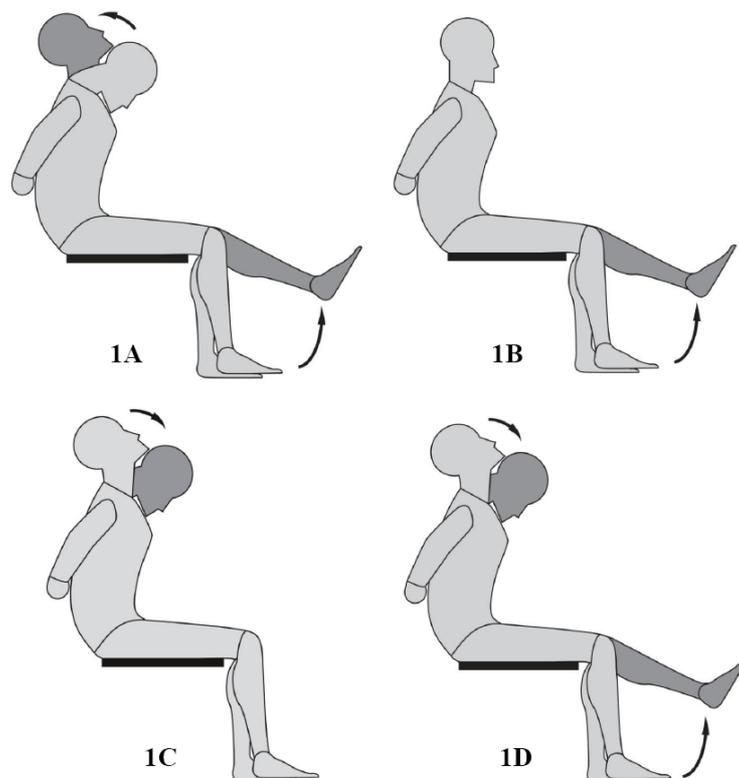
Figure 17. Slump-sitting neural mobilisation exercises (Chapter Six).
1A. Slider mobilisation. 1B. and 1C. Single-joint mobilisations. 1D. Tensioner mobilisation

In order to specifically limit movement to the knee and cervical spine, used for each of the neural mobilisations, a rigid thermoplastic ankle foot orthosis (AFO), set at neutral (0° DF), was worn each participant to eliminate the potential influence of ankle movement.

Joint movement occurred at an angular velocity of 20°/second, as set by the Biodex. The order in which the exercises were completed was randomly assigned (blinded opaque envelope selection) to avoid any possible order effects. Each participant completed all four exercises. Two repetitions of each movement were performed as practice/familiarisation trials. Then a further three repetitions of each movement were performed for data collection. There was a one minute rest period between each mobilisation exercise.

6.4.8 Statistical analysis.

To test the study hypotheses, repeated-measures analysis of variance (ANOVA) was utilised to assess differences in the dependant variable: longitudinal sciatic nerve excursion. Post-hoc pairwise comparisons of means were then performed using the Bonferroni test (Ottenbacher, 1991). Subsequently the readjusted alpha level was set was at 0.008.

The intra-rater reliability of measuring longitudinal sciatic nerve excursion from US footage using cross-correlation software was also examined. A two-way mixed intraclass correlation coefficient ($ICC_{2,1}$), with 95% confidence intervals and standard error of measurement (SEM) were calculated to determine the reliability of measurement.

Mean and range calculations were performed to establish the cervical and knee ROM for each of the neural mobilisations. Paired t-tests ($\alpha=0.05$) were used to calculate whether any differences were present for the total cervical spine and knee ROM recordings between each of the neural mobilisations exercises.

6.5 RESULTS

Of the thirty-one participants that were enrolled into the study, one participant was excluded on the basis that the sciatic nerve was not able to be maintained within the longitudinal scanning plane during data recording.

For neural mobilisations that involved cervical flexion (1C and 1D) the mean range of cervical motion was 127.8°±7.6° (38.7°±9.6° extension through to 89.1°±13.1° flexion). For the slider mobilisation (1A) that utilised cervical extension the mean range of cervical motion was 134.3°±0.2° extension (77.0°±6.2° flexion through to 57.2°±4.8° extension). There was no significant difference in the overall range of cervical spine movement between exercises using cervical extension (127.8°±7.6°) versus cervical flexion (134.3°±0.2°) ($P=0.2$).

The repeated measures ANOVA showed that there was a significant difference across the neural mobilisation exercises ($P<0.0001$). Using paired t-tests for individual comparisons, there were statistically significant differences in sciatic nerve excursion between the slider mobilisation and tensioner mobilisation (3.2mm vs. 2.6mm; $P<0.02$), between the slider mobilisation and both single-joint mobilisations (1A 3.2mm vs. 1B 2.6mm = $P<0.02$; 1A 3.2mm vs. 1C -0.1mm = $P<0.01$). There was no significant difference between 1B versus 1D.

The reliability of measuring sciatic nerve excursion across all trials for all four neural mobilisations combined was excellent with an ICC of 0.95 (95% CI, 0.93 – 0.96; SEM, 0.2mm).

6.6 DISCUSSION

In support of the study hypotheses, differences in the amount of longitudinal sciatic nerve excursion exist between different types of neural mobilisation exercises. The slider mobilisation generated significantly more sciatic nerve excursion compared to the tensioner mobilisation. Furthermore, the slider mobilisation also generated significantly greater sciatic nerve excursion compared to the single-joint mobilisations (1B and 1C). Overall these findings are generally in agreement with other work (Coppieters & Alshami, 2007; Coppieters & Butler, 2008; Coppieters et al., 2009) that has examined these techniques in the upper limb and thus provide evidence that the theoretical construct of nerve excursion during joint motion is also occurring in the lower limb. More specifically this theory states that a slider mobilisation is designed to maximise nerve excursion by simultaneously elongating the nerve bed from one end whilst releasing tension from the other. It has been postulated that a cumulative effect is then created resulting in greater nerve excursion (Coppieters et al., 2009). A single-joint mobilisation deliberately utilises movement from one end of the nerve bed only and therefore does not have the capacity to exploit any potential cumulative effect.

It is notable that no significant difference was seen between the single-joint mobilisation 1B (2.6mm) versus the tensioner mobilisation (2.6mm). It is expected that full extension of the cervical spine would allow a release of neural tension via the spinal cord and spinal nerve roots (Breig, 1978; Breig & Marions, 1963; Shacklock, 2007) which potentially allows more excursion of the sciatic nerve. However, it is also

notable that very little nerve excursion was generated with the opposite movement, full cervical flexion (1C). The tensioner mobilisation involved simultaneous elongation of the nerve bed from both ends.   However, the inclusion of cervical flexion did not significantly decrease the amount of sciatic nerve excursion, which was expected, having elongated the proximal aspect of the nerve bed. In a similar manner the single-joint mobilisation generated at the cervical spine (1C) produced minimal sciatic nerve excursion (-0.1±0.1mm).

It is not surprising that isolated cervical flexion did not cause a significant amount of sciatic nerve excursion. In view of the nervous system being a continuum, cervical flexion has been suggested to increase tension within the lumbar nerve roots resulting in an unfolding of resting slack within the nerve root (Breig & Marions, 1963; Breig & Troup, 1979a; Shacklock, 2007). Cervical flexion has been shown in research involving cadavers to cause 3-4mm cranial movement of spinal nerve roots within the thoracic spine (Breig & Marions, 1963). Cervical flexion has been widely advocated as an additional manoeuvre to the slump test in order to further tension the neural system leading to further neural sensitisation and symptom reproduction (Breig & Troup, 1979a; Butler, 2000, 2005; Shacklock, 2005a). However, it is unclear as to whether the increased neural sensitisation stems from an increase in neural tension, neural excursion and/or both. Hall, Zusman and Elvey (Hall et al., 1998) reported that the addition of cervical flexion during a straight-leg raise test (SLR) test did not show any significant change in hip flexion to first onset of manually perceived resistance in either a healthy or a lumbar radiculopathy group. These authors concluded that cervical flexion did not have a significant effect of neural tissue compliance during the SLR (Hall et al., 1998). Although nerve movement is greatest closer to the axis of joint rotation, it is generally accepted that nerve excursion becomes less the further movement is occurring from the joint (Coppieters et al., 2006; Echigo et al., 2008; Ellis et al., 2008; Hall et al., 1998;

Shacklock, 2005a), which supports the theory that the entire nervous system is continuous. Our findings are consistent with this theory in that very little sciatic nerve excursion was evident, from full cervical flexion.

Previous studies that assessed nerve excursion during neural mobilisation exercises, in cadavers (Coppieters & Alshami, 2007) and *in-vivo* (Coppieters et al., 2009), have observed greater amounts of median nerve excursion, both in absolute terms and between the different mobilisations, compared to the present study of sciatic nerve excursion. It is difficult to make direct comparisons in the current study due to the different kinematics between movement of the upper and lower limbs (e.g. in relation to joint ranges of movement). In respect to certain techniques, similarities can be seen between upper limb and lower limb data. For example, sciatic nerve excursion during the tensioner (2.6mm) is close to that seen for the median nerve during a tensioner (1.8mm) (Coppieters et al., 2009).

At this time, the clinical implication of the small magnitude of nerve excursion during neural mobilisation exercises is unclear. The key factor which limits further scrutiny of these values is the controversy that exists regarding whether reduced nerve excursion is a factor in peripheral nerve disorders and whether, if evident, neural mobilisation may influence a potential loss of nerve excursion. Although the magnitude of excursion between the different techniques appears small, given the accuracy of measurement (as seen from the ICC and SEM values), these values reflect true differences.

The one other study that has examined sciatic nerve excursion, using *in-vivo* US assessment, found similar levels of sciatic nerve excursion at the PMT (Ellis et al., 2008). However, direct comparison to this previous study is limited as differing methods were utilised. An alternative means of comparison for *in-vivo* nerve excursion

values, during neural mobilisation, is from studies performed in the upper limb (Coppieters et al., 2009; Echigo et al., 2008). From these studies, the mean median nerve excursion range that was recorded was 3.4 - 10.2 mm (Coppieters et al., 2009) and 0.8 - 3.0 mm (Echigo et al., 2008) respectively, with different methods and neural mobilisation exercises utilised.

In the current study, of the total data that was collected regarding longitudinal sciatic nerve movement, the maximum excursion of the sciatic nerve was 8.2mm. Direct comparisons of the present study to the available evidence are difficult, due to methodological variations. It is not possible to directly compare cadaveric measures of nerve excursion to the *in-vivo* situation as methods of tissue dissection and preservation have the potential to alter nerve mechanics. Unfortunately, there is a paucity of research which has examined the excursion of the sciatic nerve *in-vivo*. However, a study utilising cadavers by Beith et al. (1995) examined the increase in length of the nerve bed of the sciatic-tibial-medial plantar nerve tract and found a 42.2 ± 2.4mm (mean $\pm$ SD) increase in nerve bed length when moving the knee from 90° flexion to terminal extension. The same nerve bed increased by 6.8mm ± 0.69mm from 20° PF to plantargrade (0°) (Beith et al., 1995).

More recently, in an *in-vivo* study, Ellis et al. (2008) reported 3.5mm of longitudinal sciatic nerve movement at the PMT during full range ankle PF through to DF. Although the level of sciatic nerve excursion was greater here compared to the present study, it is difficult to directly compared the two results due to key methodological differences. For example, Ellis et al. (2008) used an upright sitting position (i.e. no slump) compared to the present study. Also the present study limited the knee ROM at -20° from terminal extension. Although speculative, if the knee had been taken into terminal extension sciatic nerve excursion may have been greater.

The neural mobilisation techniques used in this study utilised a combination of passive knee movement and active cervical spine movement. It may have been ideal to have used movements at the knee and cervical spine that were either both active or passive. In regard to using active knee movement, there are technical difficulties with using US with an actively moving limb, particularly at the PMT as active movement of the hamstrings (even in an eccentric capacity) makes it difficult to maintain US transducer contact. Implementing passive cervical spine movement through a standardised range would have been logistically difficult. However, the range of active cervical spine movement used between the different neural mobilisation exercises was not statistically different. This indicated consistency of cervical spine movement between participants across the different exercises.

It is clinically relevant to employ specific exercises that maximise their aims. For example, in conditions where nerve excursion is believed to be compromised it would be logical to utilise a neural mobilisation designed to maximise nerve excursion (e.g. a slider). Subsequently, for clinical situations which may be irritable or acute it would be logical to utilise neural mobilisation that still challenges nerve excursion, but to a lesser extent which may decrease the potential adverse influence of excessive neural tension (e.g. a nerve-gliding exercise utilising a single-joint mobilisation).

In light of the small difference in sciatic nerve excursion between the different neural mobilisations, other potential features, which were not examined in this study, may influence nerve excursion. For example, nerve strain may have a direct influence upon nerve excursion, as has been seen in a cadaver study where increased median nerve strain resulted in decreased nerve excursion (Coppieters & Butler, 2008). Likewise, symptom reproduction may also limit joint ROM and subsequently nerve excursion. Furthermore, based on these findings, it may be such that due to the small

differences seen it may be that more generic exercises are provide the same influence and features beyond those that are mechanical may be relevant. These features, along with further analysis of nerve mechanics, are worthy of consideration in regard to future research which examines neural mobilisation design. Future research that investigates the therapeutic efficacy of neural mobilisation should select specific exercises based on a better understanding of the neural mechanical effects that are likely to be exploited.

6.7 CONCLUSIONS

The findings of this study provide evidence that lower limb nerve excursion follows theory related to such movements. Different types of neural mobilisation exercises induced significantly different amounts of longitudinal sciatic nerve movement. A slider mobilisation produced the most nerve excursion compared to single-joint mobilisations and a tensioner mobilisation. It is important to take this information regarding nerve mechanics, together with similar findings from related research in the upper limb, to enable more specific design and prescription of neural mobilisation to specifically suit certain peripheral nerve disorders.

Key Points:

Findings: Different types of neural mobilisation exercises produce different amounts of longitudinal sciatic nerve excursion. The use of cervical extension during a slump slider significantly increases sciatic nerve excursion.

Implications: Knowledge regarding the varied amounts of sciatic nerve excursion that was seen with different exercises will be important to aid in specific design of neural mobilisation exercises to suit certain peripheral nerve disorders,

particularly if further research concludes that impaired nerve excursion is evident. This study does not comment on the clinical efficacy of these techniques.

Caution: Details regarding the amount of sciatic nerve excursion can only be inferred from the slump-sitting exercises that were utilised. Data on sciatic nerve excursion is only relevant to recordings taken at the level of the posterior mid-thigh and may be different at regions beyond that location.

REFERENCES

The references for this paper have been included in the full reference list of this thesis.

Chapter Seven. *In-vivo* ultrasound assessment of sciatic nerve excursion during neural mobilisation involving knee and ankle movement and the influence of cervical flexion

7.1 PRELUDE

The previous paper sought to conclude the amount of sciatic nerve excursion that can be induced with different types of slump-sitting neural mobilisation exercises (sliders and tensioners). However, the study did not seek to examine more specific biomechanical features of the sciatic nerve excursion, for example relative nerve excursion at different locations along a peripheral nerve and the effect of additional nerve tension.

The fourth aim of this thesis was to investigate the different biomechanical features of sciatic nerve excursion in response to slump-sitting neural mobilisation exercises. Neurodynamic theories suggest that peripheral nerve excursion will occur greatest the closer to the axis of joint rotation and also that nerve excursion will be directly influenced by changes in neural tension (as seen in Chapter Five).

However, these biomechanical features have not been assessed for sciatic nerve excursion during slump-sitting neural mobilisation exercises that specifically utilise cervical flexion and those that do not. A paper from this chapter has been submitted for publication in "Clinical Biomechanics".

7.2 ABSTRACT

Background: Peripheral nerve excursion is directly influenced by the location of the joint that is inducing the movement and the relative tension imposed upon the neural system. These factors are important when designing neural mobilisation

exercises in order to maximise nerve excursion in some treatments. The evidence suggests that peripheral nerve excursion is greatest closest to the axis of rotation and is directly influence by neural tension. However there is a lack of research to document these effects for the sciatic nerve *in-vivo*.

Methods: A single-group, within subject study was conducted utilising high-resolution ultrasound imaging, and frame-by-frame cross-correlation analysis to assess sciatic nerve excursion. Imaging of the sciatic nerve was at the level of the posterior mid-thigh. Different neural mobilisation exercises, performed in slump-sitting, were examined inducing movement at the knee or ankle and with or without cervical flexion.

Findings: A one-ended knee slider produced significantly greater ($P<0.0001$) distal sciatic nerve excursion (mean 2.63mm (SD 1.44)) compared to a one-ended ankle slider (-0.17mm, SD 0.48). The addition of cervical flexion to a one-ended ankle slider resulted in a significant increase in proximal sciatic nerve excursion from 0.17mm (SD 0.48) to 0.39mm (SD 0.50) ($P<0.0001$). However there was no significant change ($P=0.70$) in sciatic nerve excursion with the addition of cervical flexion to the one-ended knee slider (2.63mm (SD 1.43) versus 2.56mm (SD 1.49).

Interpretation: For neural mobilisation exercises designed to mobilise the sciatic nerve, in slump-sitting greater nerve excursion will occur using movement at the knee joint. However, the position of the cervical spine (whether in neutral or flexed) does not significantly alter distal sciatic nerve excursion.

Keywords: neural mobilisation, nerve biomechanics, diagnostic ultrasound

7.3 INTRODUCTION

Neural mobilisation attempts to restore movement between neural tissues and their surrounding mechanical interfaces thereby reducing extrinsic and intrinsic pressures to promote optimum neural function (Brown et al., 2011; Butler, 2000; Butler et al., 1994; Ellis et al., 2008; Gifford, 1998; Herrington, 2006; Kitteringham, 1996; Shacklock, 1995b, 2005a). As neural mobilisation aims to influence nerve movement, an understanding of nerve mechanics is important. However at present there is scant evidence which has examined the biomechanical effect of neural mobilisation upon nerve excursion. Such work could be utilised to guide the choice and design of neural mobilisation exercises.

Several important biomechanical features of the nervous system need to be considered when assessing neural mobilisation. That the nervous system is a continual system requires careful clinical reasoning for the most appropriate technique to be chosen. For example, theories suggest that the greatest amount of nerve excursion will be induced closest to the axis of rotation that is initiating the movement (Boyd et al., 2005; Dilley et al., 2008; Dilley et al., 2007; Echigo et al., 2008; Ellis et al., 2008; Goddard & Reid, 1965; Julius et al., 2004; McLellan & Swash, 1976; Wilgis & Murphy, 1986). However as joint movement continues, there will be a continuation of nerve excursion at more distant locations although progressively less the further from the axis of joint movement (Dilley et al., 2003; Dilley et al., 2008; Echigo et al., 2008; Ellis et al., 2008; Julius et al., 2004; Reid, 1960; Wright et al., 2001).

A further consideration is the influence of nerve tension. Nerve excursion that is present with single joint movement will diminish with additional joint movements that increase tension (Coppieters & Alshami, 2007; Coppieters et al., 2006; Coppieters et al., 2009; Wright et al., 1996). With increasing tension the elastic limits of the neural

connective tissues are challenged resulting in a decrease in relative excursion (Coppieters et al., 2006; Dilley et al., 2003; Dilley et al., 2007; Kwan et al., 1992).

The clinical implication of relative tension versus excursion is significant when utilising different types of neural mobilisation. The potential exists for unwanted cumulative increases in tension or excursion in regions beyond the targeted area may occur (Alshami et al., 2008; Coppieters & Butler, 2008; Topp & Boyd, 2006). For example, the inclusion of additional joint movements (i.e. from the cervical spine) which increase nerve tension, during a neural mobilisation exercise, may be contraindicated in acute conditions (Coppieters & Butler, 2008). The location or sequence of joint movement will determine the balance between nerve excursion versus nerve strain during a neural mobilisation exercise (Coppieters & Alshami, 2007; Coppieters & Butler, 2008). It is reasonable to suggest that ensuring this balance is appropriate for a specific condition may dictate the potential therapeutic efficacy of neural mobilisation.

The objective of this study was to utilise high-resolution USI to examine specific biomechanical effects of different neural mobilisation exercises upon longitudinal sciatic nerve excursion. Guided by a premise established in the upper limb that greater nerve excursion occurs closest to the axis of joint rotation, the first hypothesis was that sciatic nerve excursion, measured at the posterior mid-thigh (PMT), will be greater for neural mobilisation exercises that utilise the knee joint compared to those utilising the ankle joint. Furthermore, on the basis that increased neural tension will decrease the relative amount of nerve excursion, the second hypothesis was that increased neural tension via the addition of cervical flexion to neural mobilisation exercises will decrease the amount of sciatic nerve excursion irrespective of the joint movement used to induce sciatic nerve excursion (i.e. knee or ankle movements).

7.4 MATERIALS AND METHODS

7.4.1 Participants

Thirty healthy participants (21 females, 9 males) (range 21-61 years; mean (SD) age 29 (9) years, height 170.3cm (7.6), weight 68.4kg (13.2), BMI 23.4 (3.1)) volunteered for this study. The inclusion criteria stipulated that participants did not have sciatic nerve dysfunction so that normal sciatic nerve mechanics could be assessed. The exclusion criteria were a history of significant/major trauma or surgery to the lumbar, hip, buttock (gluteal) or hamstring (posterior thigh) regions, symptoms consistent with sciatic nerve impairment (i.e. paraesthesias, weakness, etc.), a positive slump test (as described by Butler, 2000) and conditions which may alter the function of the nervous system, for example, diabetes.

A power analysis and sample size calculation was performed using G*Power 3, online power analysis software (Erdfelder et al., 1996; Faul et al., 2007) on the data of fifteen participants. The dependent variable was mean sciatic nerve excursion between the exercises generated at the knee (one-ended knee slider, OEKS) and generated at the ankle (one-ended ankle slider, OEAS). To establish a significant difference for this variable, with the power set at 0.8 and alpha level set at 0.05 the number of participants required was four. Following the pilot study and power analysis, a review of the procedures and methods used was conducted. From this it was deemed that the procedures were appropriate and no changes were necessary. Prior to the power analysis, participant recruitment had already found another 15 participants. Based on the conclusion that no procedural changes were to be made, the data of the 15 participants from the pilot study were pooled with the remaining 15 participants.

Participants were provided with both written and verbal information concerning the testing procedures. Informed consent was given by all participants. The study was

approved by the Auckland University of Technology Ethics Committee (AUTEC) (see Appendix 8).

7.4.2 Participant set-up

A Biodex system 3 isokinetic dynamometer (Biodex Medical, Shirley, NY, USA) was used to provide the passive knee and ankle movements during the neural mobilisation exercises. Each participant was asked to sit on the Biodex seat and relax, flexing through their spine to adopt a slumped position. This position was maintained with contact of the sternum against a 45cm diameter Swiss ball which was placed on the participants lap. A seatbelt was utilised to maintain this position.

7.4.3 Joint ROM analysis.

ROM at the cervical spine, knee and ankle joints was measured with a 3-Space Fastrak (Polhemus Inc., Colchester, Vermont, USA) electromagnetic motion tracking system. The Fastrak system monitors the position of four separate sensors in respect to a source unit emitting a low-intensity electromagnetic field. The Fastrak system has been shown to be accurate to within 0.2° when recording spinal motion (Pearcy & Hindle, 1989).

For the cervical spine, sensor 1 was placed at the middle of the forehead (in line with the bridge of the nose) using an adjustable elastic headband and sensor 2 was placed over the spinous process of C7 (Amiri et al., 2003; Dall'Alba et al., 2001; Jasiewicz et al., 2007). For the knee, both sensors were placed on the lateral aspect of the leg, sensor 1 was 100mm above the lateral joint line and sensor 2 was 100mm below the joint line (Bullock-Saxton et al., 2001; Laprade & Lee, 2005). For the ankle, sensor

1 was placed on the tibia, mid-way between the lateral malleolus and lateral knee joint line, and sensor 2 was placed along the lateral aspect of the base of the foot just posterior to the base of the 5th metatarsal.

LabVIEW 2009 (Version 9.0f2, National Instruments, Austin, TX, USA) computer software was utilised to allow real-time visualisation and recording of the motion trace from the Fastrak. The joint angle data recorded from the cervical, knee and ankle were then synchronised off-line with the recorded ultrasound (US) sequences.

7.4.4 Ultrasound imaging

Excursion of the sciatic nerve was assessed at the level of the PMT (half-way between the gluteal crease and popliteal crease), a position that has high reliability when measuring sciatic nerve excursion (Ellis et al., 2008). Initial transverse imaging at the PMT allowed localisation of the sciatic nerve. Once identified, the US transducer was rotated into the longitudinal plane (Coppieters et al., 2009; Echigo et al., 2008). An experienced sonographer performed all US scans. B-mode real time US scanning was performed using a Philips iU22 (Philips Medical Systems Company, Eindhoven, The Netherlands) US machine with a 12-5MHz, 50mm, linear array transducer. An US sequence of the nerve in longitudinal plane was recorded for each exercise trial. Each US video sequence was three seconds long captured at 30 frames per second.

Each USI video sequence was converted to digital format (bitmaps). The image size for each of the frames was 800x600 pixels. ImageJ (Version 1.42, National Institute of Health, Maryland, USA) digital image analysis software was used to calculate the image resolution and the scale conversion for pixels to millimetres.

Each video sequence was analysed using frame-by-frame cross-correlation analysis software developed in Matlab (Mathworks, USA). This method employs a cross-correlation algorithm to determine relative movement of speckle features between successive frames in a sequence of US images (Dilley et al., 2001). This method has proved to be a highly reliable method of assessment of nerve motion (Coppieters et al., 2009; Dilley et al., 2001; Ellis et al., 2008).

Each US video sequence was reviewed for clear pixilation and clear identification of the sciatic nerve throughout the three second duration. Of the video sequences that met these criteria, two were randomly chosen for each of the four neural mobilisations, per participant, for cross-correlation analysis.

7.4.5 Neural mobilisation exercises

Four neural mobilisation exercises were assessed (Figure 18). These were:

1. One-ended knee slider (OEKS): passive knee extension from 80º knee flexion to 20° flexion. The cervical spine was maintained steady by instructing each participant to look ahead and to fix their gaze upon a stationary object.

2. One-ended ankle slider (OEAS): passive ankle dorsiflexion (DF) from 30° plantarflexion (PF) to neutral (0° DF). The cervical spine was maintained steady by instructing each participant to look ahead and to fix their gaze upon a stationary object.

3. Knee Tensioner (KT): Simultaneous passive knee extension from 80º flexion to 20° flexion with active cervical flexion from full extension to full flexion.

4. Ankle tensioner (AT): Simultaneous passive ankle DF from 30° PF to neutral (0° DF) with active cervical flexion from full extension to full flexion.
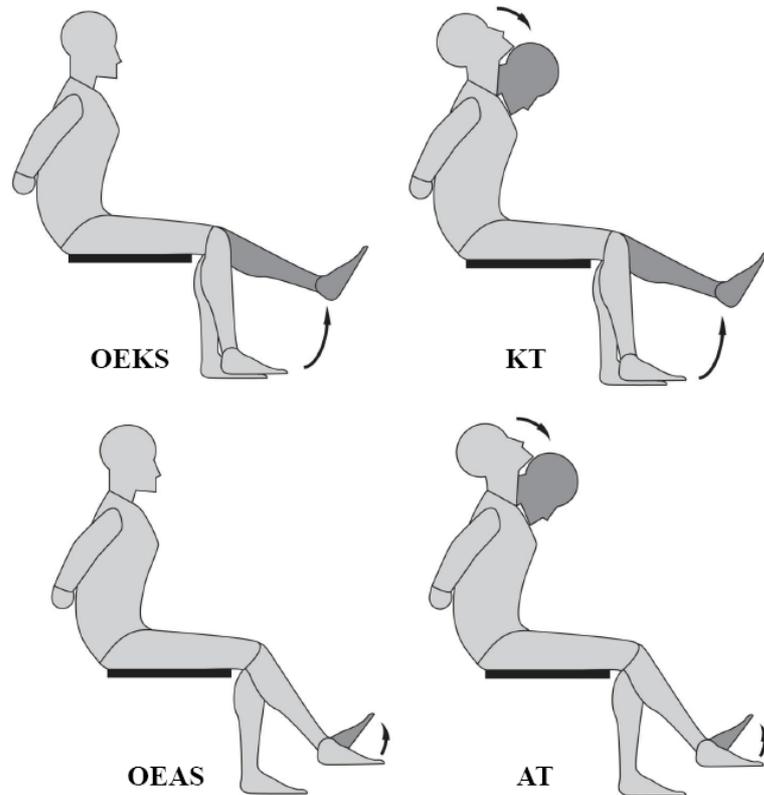
Figure 18. Slump-sitting neural mobilisation exercises (Chapter Seven).
OEKS: 1-ended knee slider; KT: knee tensioner; OEAS: 1-ended ankle slider; AT: ankle tensioner

For the OEKS and KT the Biodex moved the knee joint between 80° flexion and 20° flexion (0° equivalent to terminal knee extension). Knee joint movement was set at a joint angular velocity of 20°/second. The ankle/foot was held in a rigid thermoplastic ankle foot orthosis (AFO), set at 90°. This was standardised across all participants over all trials.

For the OEAS and AT, the Biodex passively moved the ankle from 30° PF to 0°, at a velocity of 10°/second. The knee joint was held at 50° flexion by the adjustable arm of the Biodex. Once again, this was standardised for all participants over all trials.

A randomisation procedure was utilised for the order of exercises undertaken. Each participant completed all four exercises. Two repetitions of each movement were performed as practice/familiarisation trials. Then a further three repetitions of each movement were performed for data collection with a one minute rest period between each mobilisation exercise.

All saved US sequences were transferred to a computer. To ensure blinding of the measurements, the researcher who carried out all of the US sequence analyses was blinded to knowledge concerning both the participant and exercises.

7.4.6 Statistical analysis

Repeated-measures analysis of variance (ANOVA) was utilised to detect differences in sciatic nerve excursion across the four neural mobilisations. To specifically test the primary study hypothesis, paired t-tests were used to calculate whether any differences were seen between the OEKS versus the OEAS. To specifically test the secondary study hypothesis, paired t-tests were used to calculate whether any differences were seen between the OEKS versus the KT and OEAS versus the AT. The alpha level was set at 0.05.

7.5 RESULTS

For neural mobilisations that involved cervical flexion (KT and AT) the mean range of cervical motion was 134.3° (SD 1.8°) (from 38.7° (SD 11.6°) extension to 96.5° (SD 13.4°) flexion).

A positive value indicated nerve excursion in a distal direction (towards the knee) whilst a negative value indicated excursion in a proximal direction (towards the hip). A significant difference in the amount of sciatic nerve excursion between all four neural mobilisation exercises ($P<0.0001$) was found. A statistically significant difference was seen in sciatic nerve excursion between the OEKS (2.63mm (SD 1.43)) versus OEAS (-0.17mm (SD 0.48)) ($P<0.0001$). There was a statistically significant difference in sciatic nerve excursion between the OEAS (-0.17mm (SD 0.48)) and AT (-0.39mm (SD 0.50)) ($P<0.0001$). With the addition of cervical flexion sciatic nerve excursion between the OEKS and KT was unchanged ($P=0.70$) (Figure 19).
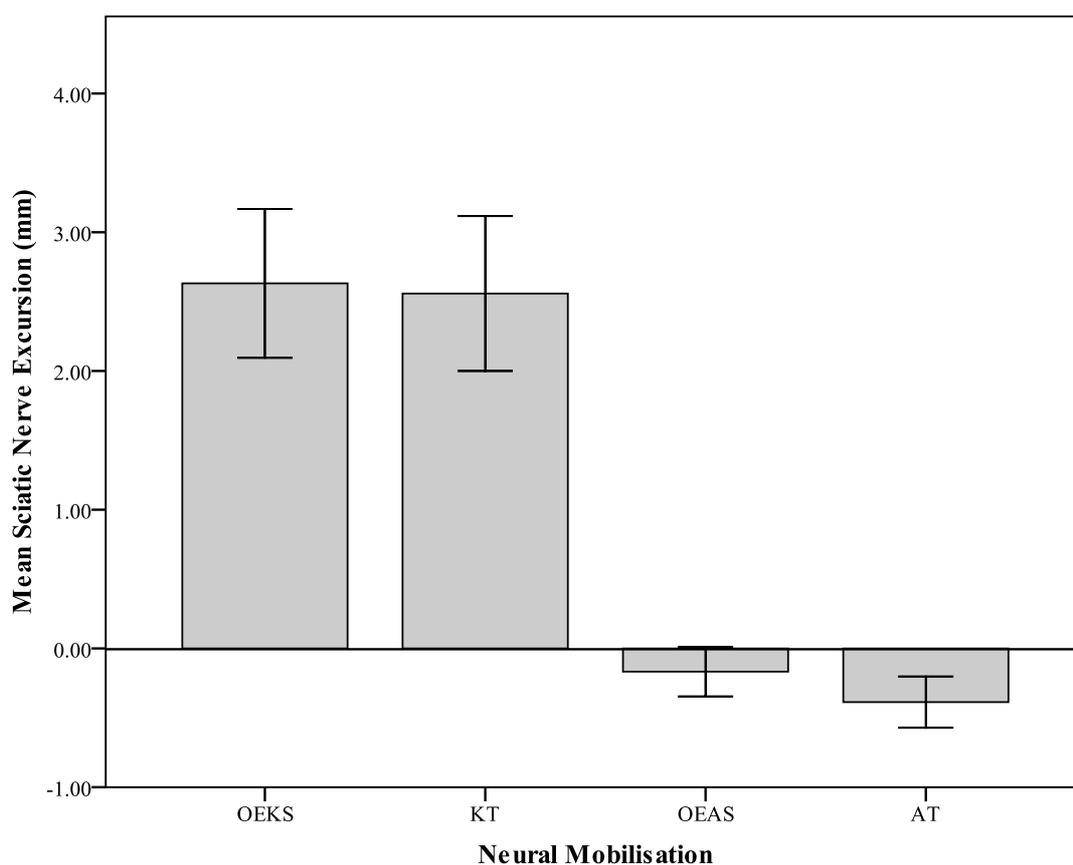
Figure 19. Comparison of mean sciatic nerve excursion (mm) between all neural mobilisation exercises. (Error bars represent 95% confidence intervals (CI)). OEKS: 1-ended knee slider; KT: knee tensioner; OEAS: 1-ended ankle slider; AT: ankle tensioner. A positive value indicates nerve excursion in a distal direction (towards the knee) whilst a negative value indicates excursion in a proximal direction (towards the hip).

7.6 DISCUSSION

In support of the theory that the nervous system is a continual system, the findings do suggest that nerve excursion in the sciatic nerve (at the PMT) will occur with movement induced by both the knee and ankle. As the knee joint is closer to the scanning location (PMT) the finding that significantly more sciatic nerve excursion occurred from movement at the knee (OEKS, 2.63mm) compared to the ankle (OEAS, -0.17mm) supports both the primary hypothesis and also previous research findings. That is, several cadaver studies have concluded that sciatic nerve excursion is greatest

the closer to the axis of joint rotation (Coppieters et al., 2006; Goddard & Reid, 1965; Reid, 1960; Smith, 1956). However this phenomenon has not been confirmed, prior to this study, *in-vivo* when examining sciatic nerve excursion induced from movements at the knee and ankle.

To the authors' knowledge, no previous research has examined the influence of increased neural tension, imposed by the addition of cervical flexion, upon sciatic nerve excursion during neural mobilisation exercises in slump-sitting. A significant difference in nerve excursion was seen when cervical flexion was added to the ankle exercise (OEAS -0.17mm versus AT -0.39mm). However no significant difference was seen in nerve excursion when cervical flexion was added to the knee exercise (OEKS 2.63mm versus KT 2.56mm). Therefore it has been possible to accept the secondary hypothesis in regard mobilisations utilising ankle movement, however the hypothesis has been rejected in regard to mobilisations utilising knee movement.

It has been postulated that progressive addition of neural load will cause less nerve excursion and more nerve tension to occur (Coppieters et al., 2006; Dilley et al., 2003; Kwan et al., 1992; Topp & Boyd, 2006). *In-vivo* studies have concluded that knee extension, during a slump test, decreases when cervical flexion is added to the test (Fidel et al., 1996; Herrington et al., 2008; Johnson & Chiarello, 1997; Tucker et al., 2007; Yeung et al., 1997) however these studies have not examined nerve motion directly. The explanation given for the reduction in knee extension is that the addition of cervical flexion imposes additional tension upon the neuromeningeal structures at the spinal cord and nerve roots leading to a reciprocal increase in tension further down to the sciatic nerve tract (Fidel et al., 1996; Herrington et al., 2008; Johnson & Chiarello, 1997; Tucker et al., 2007; Yeung et al., 1997). Others (Breig, 1978; Breig & Marions, 1963; Breig & Troup, 1979b) have observed that cervical flexion increases general

neural tension to an extent whereby excursion of the lumbosacral nerve roots has been seen in cadaver studies. It is possible that the non-significant decrease in nerve excursion seen by incorporating cervical flexion in the KT occurred as further tension was being imposed on an already loaded system which would have not allowed significant changes in nerve excursion. If this had been the case then sufficient tension may not have been added to result in a decrease in nerve excursion.

The ankle joint movement used during the OEAS and AT (30° DF) was half that used at the knee joint for the OEKS and KT (60° extension). This smaller joint range may not have exposed the sciatic nerve tract to significant tension. Several studies have reported significant reductions in either hip flexion angle (during a straight-leg raise test) (Boland & Adams, 2000; Gajdosik et al., 1985; Herrington et al., 2008) or knee extension angle (during a slump test) (Johnson & Chiarello, 1997; Yeung et al., 1997) when the ankle is held in DF compared to when relaxed in PF. These studies all used end-range DF as the test position, which is significantly more than the range used in the present study. It is possible that the smaller ankle ROM used in the present study did not start to challenge nerve mobility to the same extent as seen for knee movement. This may have resulted in less neural tension generated.

Of note is that the values of sciatic nerve excursion recorded from OEAS and AT are negative. Negative values correspond to nerve excursion towards the hip joint (proximal excursion). Several authors have suggested that cervical flexion (Breig & Marions, 1963; Breig & Troup, 1979b; Lew, Morrow, Lew, & Fairbank, 1994; Shacklock, 2007; Troup, 1986) and general spinal flexion (Inman & Saunders, 1941; Penning & Wilmink, 1981; Shacklock, 2007) induces cephalic movement of the lumbar nerve roots. The increased sciatic nerve excursion seen in the AT, with movement of the nerve towards the hip, may have resulted from cephalically directed tension and

movement generated with cervical flexion via the spinal cord, lumbosacral nerve roots and sciatic nerve.

A limitation of this study is the possibility that greater nerve excursion occurred during the OEKS due to the greater ROM used at the knee compared to the ankle for the OEAS. It was not possible to standardise the ROM at both joints to the same range due to concerns over limiting the potential of excessive neural stretch that may have occurred with ankle DF beyond a neutral position. As slump-sitting positions increase general load on the nervous system (Fidel et al., 1996; Slater et al., 1994) to avoid potential adverse effects of excessive increases in neural tension, the Biodex dynamometer was set to ranges below that of maximum knee and ankle joint movement. Clinically it would be common practice to use a range of joint movement during a neural mobilisation exercise up to or just prior to a level which would induce clinical symptoms (Shacklock, 2005a). The exercises used in this study did not attempt to use ranges of movement whereby clinical symptoms were reported and so must be viewed in context. A further limitation of this study was the use of different velocities in regard to the joint movement (20°/second for the knee and 10°/second for the ankle). This was done to ensure that the total joint movements were conducted over the same testing period (three seconds). It cannot be discounted that differences in joint angular velocity may influence nevre excursion.

7.7 CONCLUSION

Significantly greater sciatic nerve excursion is generated in slump-sitting neural mobilisation exercises, at the level of the posterior mid-thigh, when using knee as opposed to ankle movements. This supports previous research which reports that peripheral nerve excursion is greatest in the region closest to the joint movement used.

There does not appear to be a significant difference in distal sciatic nerve excursion when adopting either a neutral or a flexed cervical position during slump-sitting neural mobilisation exercises.

REFERENCES

The references for this paper have been included in the full reference list of this thesis.

Chapter Eight. Identifying the sequence of sciatic nerve excursion during different neural mobilisation exercises: an *in-vivo* study utilising ultrasound imaging

8.1 PRELUDE

Although the previous two studies (Chapters Six and Seven) have quantified varied amounts of sciatic nerve excursion during different neural mobilisation exercises, neither study has examined whether there is a specific sequence of sciatic nerve excursion. The identification of a sequence of sciatic nerve excursion will be important for the specific design of neural mobilisation exercises, particularly those that are intended to maximise nerve excursion.

It has been suggested that peripheral nerves demonstrate a sigmoidal pattern of excursion when exposed to movement from the body (Topp & Boyd, 2006). A sequence of peripheral nerve excursion has been observed in the lower limb of cadavers (Breig & Troup, 1979b; Charnley, 1951; Fahrni, 1966; Goddard & Reid, 1965; Inman & Saunders, 1941) and *in-vivo* in the upper limb (Dilley et al., 2003; Dilley et al., 2008; Dilley et al., 2007). The assessment of a sequence of sciatic nerve excursion, during neural mobilisation, has not been examined. An important aspect of the fourth aim of this thesis was to examine whether a sequence of sciatic nerve excursion could be identified during different slump-sitting neural mobilisation exercises.

The observation of a sequence of nerve excursion in the lower limb would be important to the design and prescription of neural mobilisation exercises. It would allow an appreciation of the point, during the performance of neural mobilisation exercises, that optimum nerve excursion is occurring. A paper from this chapter has been submitted for publication in the "Journal of Orthopaedic and Sports Physical Therapy".

8.2 ABSTRACT

Study Design: A controlled laboratory study using a single-group, within-subject comparison.

Objectives: To determine whether the sciatic nerve exhibits a sigmoidal sequence of excursion *in-vivo* during different types of neural mobilisation exercises.

Background: Research suggests that peripheral nerves exhibit a sigmoidal sequence of excursion during limb movements. Initially slack is taken up before nerve excursion occurs followed by a period of elongation. Knowledge of such a sequence during neural mobilisation exercises will enhance their design to maximise nerve excursion.

Methods: High-resolution ultrasound imaging of sciatic nerve excursion was synchronised with cervical and knee joint range of movement data during the performance of three different neural mobilisation exercises in thirty healthy participants. Imaging of the sciatic nerve was at the level of the posterior mid-thigh. Graphical and descriptive analysis was utilised to identify the sequence of nerve excursion during each neural mobilisation exercise.

Results: A sigmoidal sequence of nerve excursion was identified for the two-ended slump slider and slump tensioner exercises but not the one-ended slump slider. The point of greatest nerve excursion, for all exercises, occurred once 73-80% of each exercise had been completed (during a three second exercise period). Once 67% of the exercise was complete, the amount of nerve excursion was significantly greater for the two-ended slump slider compared to the one-ended slump slider ($P<0.05$). Once 90% of each exercise was complete, the amount of nerve excursion was significantly greater for the two-ended slump slider compared to the slump tensioner ($P<0.05$).

Conclusion: These findings support previous cadaveric research that sciatic nerve excursion exhibits a sigmoidal sequence during a two-ended slump slider and slump tensioner neural mobilisation exercises. Appreciation of the sequence of nerve excursion during different neural mobilisation exercises will enhance their prescription for conditions where nerve excursion is compromised.

Keywords: ultrasound imaging, nerve biomechanics, nerve sliding

8.3 INTRODUCTION

In order to cope with mechanical stresses that are imposed from adjacent tissues, the nervous system must possess specific biomechanical features to maintain the integrity of its neurophysiological function (Kwan et al., 1992). These biomechanical features ensure that the nervous system can operate optimally within an environment where it is constantly challenged by movements and postures of the body. One of these biomechanical features is the ability of a peripheral nerve to glide and slide against its surrounding mechanical interface, also known as nerve excursion (Boyd et al., 2005; Dilley et al., 2003; Erel et al., 2003; McLellan, 1975; McLellan & Swash, 1976).

There is a large body of evidence that details the magnitude of nerve excursion. However there is less research concerning the sequence of nerve excursion. Based on the results of studies which have examined the viscoelastic properties of peripheral nerves, it has been suggested that a nerve will initially go through a period of unfolding followed by sliding once the inherent slack of the nerve is taken up. Thereafter elongation occurs and the nerve is stretched towards its elastic limits (Topp & Boyd, 2006).

In respect to neural mobilisation, it is critical to have information regarding the degree and sequence of nerve excursion in order to design the best exercise to suit a specific condition. For example, 'sliders' can be specifically utilised to maximise nerve excursion in conditions where nerve excursion is compromised (Butler, 2000; Coppieters & Alshami, 2007; Coppieters & Butler, 2008; Coppieters et al., 2009; Shacklock, 2005a). However these arguments have been based on mean levels of nerve excursion rather than reflection on the pattern or sequence of nerve excursion.

There is information available about the sequence of nerve excursion within the literature which is not specific to neural mobilisation. When the nerve bed is in a shortened position, the associated nerve is unloaded and exposed to minimal, if any, tension (Dilley et al., 2007; Julius et al., 2004; Kleinrensink et al., 1995). This unloading or slackness is important to allow enough nerve length to accommodate large limb movements (Dilley et al., 2003; Dilley et al., 2007).

For example, very little longitudinal excursion of the median (Dilley et al., 2003) and ulnar (Dilley et al., 2007) nerves was evident within the first 50° of shoulder abduction. However, beyond 50° significantly greater median (Dilley et al., 2003) and ulnar (Dilley et al., 2007) nerve excursion occured to allow further upper limb motion. Likewise, excursion of the median nerve during elbow extension (90° flexion to extension) did not occur until extension was past 53° (Dilley et al., 2008). Other significant areas of nerve slack have been described at the spinal nerve roots and associated dura (Breig & Marions, 1963), elbow (Byl et al., 2002; Dilley et al., 2003; Dilley et al., 2007; Grewal et al., 2000; Wright et al., 1996), wrist (Wright et al., 1996), hip (Charnley, 1951; Fahrni, 1966; Goddard & Reid, 1965; Inman & Saunders, 1941; Shacklock, 2005b, 2007) and knee (Ellis et al., 2008).

As joint motion increases, eventually there will be relatively less sliding movement and greater nerve elongation (Charnley, 1951; Dilley et al., 2007; Kwan et al., 1992; McLellan & Swash, 1976; Shacklock, 1995b, 2005a; Topp & Boyd, 2006). It is during such elongation that nerve tension and intraneural pressures exponentially increase (Bay et al., 1997; Charnley, 1951; Kwan et al., 1992; Millesi et al., 1995; Sunderland, 1990; Sunderland & Bradley, 1961a). Beyond the elastic capabilities of the neural connective tissues, the peripheral nerve will become damaged (Sunderland, 1990; Sunderland & Bradley, 1961a; Topp & Boyd, 2006).

This sequence of nerve movement has been illustrated in several studies which have examined the sciatic and lumbosacral nerve roots. Human cadaveric experiments have shown that during the straight-leg raise (SLR) test the sciatic nerve initially started to slide after some degree of hip flexion [after the first 5° of hip flexion (Goddard & Reid, 1965) or following 15-30º of hip flexion (Breig & Troup, 1979b; Charnley, 1951; Fahrni, 1966; Inman & Saunders, 1941)]. As the SLR continued progressively less sliding and more elongation occurred, so that by greater than 70° of hip flexion elongation dominated (Charnley, 1951; Fahrni, 1966; Gajdosik et al., 1985; Goddard & Reid, 1965). A similar trend has been seen in excursion of the lumbosacral nerve roots during the SLR in cadavers. The nerve roots remained slack and still during the first 30-40° of hip flexion, then root excursion was evident with two-thirds having been completed at 60° hip flexion, and beyond 70° hip flexion excursion tapered off and elongation was evident (Ko et al., 2006).

Demonstration of the same phenomenon has been shown with *in-vivo* analysis but only in the upper limb. Greater median nerve excursion was reported in the upper arm (10mm) compared to the forearm (3mm) as the elbow initially extended (i.e. from 90° to 50° flexion). However from 50° flexion to full elbow extension the nerve

became tensioned, nerve excursion diminished, and elongation occurred in both the upper arm and forearm (Dilley et al., 2003). This same phenomenon was observed with nerve movement induced by wrist extension. Here, significant median nerve excursion was not seen at the upper arm compared to the forearm until the slack of the median nerve was taken up by extending the elbow (Dilley et al., 2003). When analysing median nerve excursion and strain during different types of neural mobilisation exercises, a clear pattern had been found showing that sliding techniques resulted in greater median nerve excursion and less strain whereas tensioning techniques resulted in comparatively less nerve excursion but greater nerve tension (Coppieters & Alshami, 2007; Coppieters & Butler, 2008).

The objective of this study was to utilise high-resolution ultrasound imaging (USI) to examine sciatic nerve excursion during different neural mobilisation exercises. Sciatic nerve excursion data was synchronised with joint range of movement (ROM) data in order to ascertain patterns of nerve excursion during each exercise. The primary hypothesis of this study was that sciatic nerve excursion would exhibit a sigmoidal pattern of movement indicating unfolding of slack (i.e. minimal initial nerve excursion) followed by nerve sliding (i.e. substantial nerve excursion) followed by nerve elongation (i.e. minimal nerve excursion). A secondary hypothesis was that the greatest rate of sciatic nerve excursion would be seen during the middle stages of the neural mobilisation.

8.4 METHODS

8.4.1 Participants.

Thirty healthy participants (21 females, 9 males) (range 21-61 years; mean±SD age 29±9 years, height 170.3cm±7.6, weight 68.4kg±13.2, BMI 23.4±3.1) volunteered for this study. Participants were included if they were over the age of eighteen and did not have any clinical signs or symptoms indicating sciatic nerve dysfunction. The deliberate intention was to include healthy participants to assess normal nerve mechanics.

Therefore participants were excluded if they had a history of significant/major trauma or surgery to the lumbar, hip, buttock (gluteal) or hamstring (posterior thigh) regions; symptoms consistent with sciatic nerve impairment (i.e. paraesthesias, weakness, etc.); a positive slump test (a test which determines mechanosensitivity of the sciatic nerve and its associated branches) as described by Butler (2000). Participants were also excluded if they had a neurological condition or other disorders which might alter the function of the nervous system, for example diabetes.

Participants were provided with both written and verbal information concerning the testing procedures. Informed consent was provided by all participants. Ethics approval was sought and approved by AUTEC (Auckland University of Technology Ethics Committee) (see Appendix 8).

8.4.2 Participant position.

A Biodex system 3 isokinetic dynamometer (Biodex Medical, Shirley, NY, USA) was used to provide passive knee extension during all neural mobilisation exercises. This allowed a consistent participant position and standardised knee

movement. Participants were positioned on the Biodex seat. A seated slump position was adopted which involved relaxation forwards into a flexed position through the length of the spine. This position was maintained via a belt, placed along the length of the spine, which held the torso (via the sternum) against a 45cm diameter Swiss ball.

8.4.3 Joint ROM analysis.

Cervical spine and knee joint ROM was measured with a 3-Space Fastrak (Polhemus Inc., Colchester, Vermont, USA) electromagnetic motion tracking system. The Fastrak system monitors the position of four separate sensors in respect to a source unit emitting a low-intensity electromagnetic field, within six-degrees of freedom in three dimensions. Angular and linear displacements are measured by recording the position and orientation of each of the sensors within the electromagnetic field. The Fastrak system has been shown to be accurate to within ±0.2° when recording spinal motion (Pearcy & Hindle, 1989).

For cervical ROM measurements, Sensor 1 was placed at the middle of the forehead (in line with the bridge of the nose) (Amiri et al., 2003; Dall'Alba et al., 2001; Jasiewicz et al., 2007; Sterling et al., 2002; Trott et al., 1996) using an adjustable elastic headband. Sensor 2 was placed over the spinous process of C7, and secured with double sided tape. For knee ROM measurements both sensors were secured (using double sided tape) on the lateral aspect of the leg, Sensor 1 100mm above the lateral joint line and Sensor 2 100mm below the joint line (Bullock-Saxton et al., 2001).

The Fastrak was linked to a computer which recorded the signals at 30 samples per second when using four sensors. LabVIEW 2009 (Version 9.0f2, National Instruments, Austin, TX, USA) computer software was utilised to allow real-time

visualisation and recording of the motion trace. The cervical spine and knee ROM data were captured onto a computer and then synchronised, off-line, to the recorded USI sequences.

8.4.4 Neural mobilisation exercises.

1. Two-ended knee slider (TEKS): Simultaneous passive knee extension (from 80º flexion to 20° flexion - loading of the sciatic nerve caudally via the tibial nerve) with active cervical extension (from full cervical flexion to full cervical extension - unloading of nervous system cranially).

2. One-ended knee slider (OEKS): Passive knee extension (from 80º flexion to 20° flexion - loading of the sciatic nerve caudally via the tibial nerve). Each participant was instructed to look straight ahead in order to maintain their cervical spine in a neutral position.

3. Knee tensioner (KT): Simultaneous passive knee extension (from 80º flexion to 20° flexion - loading of the sciatic nerve caudally via the tibial nerve) with active cervical flexion (from full cervical extension to full cervical flexion - loading of nervous system cranially).
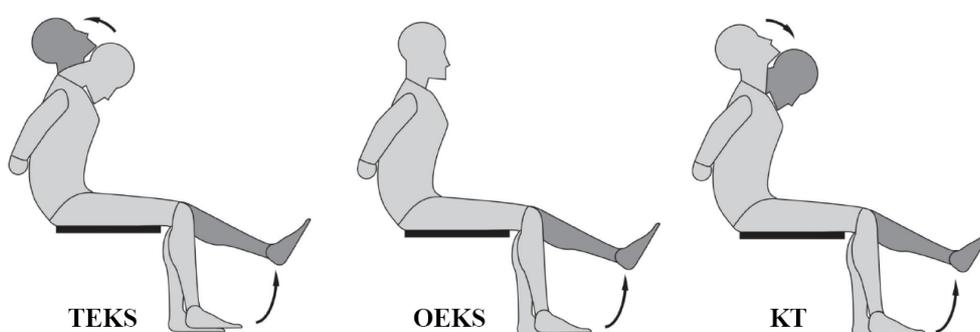
Figure 20. Slump-sitting neural mobilisation exercises (Chapter Eight).
TEKS: 2-ended knee slider; OEKS: 1-ended knee slider; KT: knee tensioner

To prevent movement at the ankle and foot a rigid thermoplastic ankle-foot orthosis, set at neutral (0° dorsiflexion) was worn by each participant. The Biodex performed the passive knee extension (60°) at a set angular velocity of 20°/second. Taking into account acceleration and deceleration of the Biodex, when creating the movement, constant velocity was maintained between 0.5 seconds and 2.7 seconds (see the grey shaded area on Figures 21-24).

The order in which the exercises were completed was randomly assigned. Each participant completed all three exercises. Two repetitions of each movement were performed as practice/familiarisation trials. Then a further three repetitions of each movement were performed for data collection. There was a one minute rest period between each mobilisation exercise.

8.4.5 Ultrasound imaging and ultrasound video selection criteria.

Excursion of the sciatic nerve was assessed at the level of the PMT (half-way between the gluteal crease and popliteal crease). High levels of reliability have been reported for this measurement point (Ellis et al., 2008). Initial transverse imaging at the PMT allowed localisation of the sciatic nerve. Once identified, the ultrasound transducer was rotated into the longitudinal plane. This method of peripheral nerve location is recommended (Coppieters et al., 2009; Echigo et al., 2008). A sonographer with five years experience performed all ultrasound scans. The sonographer was blinded to all ultrasound measurements taken.

B-mode real time ultrasound scanning was performed using a Philips iU22 (Philips Medical Systems Company, Eindhoven, The Netherlands) ultrasound machine

with a 12-5 MHz, 50mm, linear array transducer. An ultrasound sequence of the nerve in longitudinal plane was recorded for each exercise trial.

Each ultrasound video sequence was converted to digital format (bitmaps). The image size for each of the frames was 800x600 pixels. ImageJ (Version 1.42, National Institute of Health, Maryland, USA) digital image analysis software was used to calculate the image resolution and also the scale conversion for pixels to millimetres. Image resolution varied between 7.3 – 10.4 pixels/millimetre depending on the depth of ultrasound penetration required to capture the sciatic nerve.

Each ultrasound video sequence was reviewed several times. To be selected for analysis, the video sequence must have had clear pixilation and clear identification of the sciatic nerve throughout the three second duration. Of the video sequences that met these criteria, two were randomly chosen for each of the three neural mobilisations, per participant, for cross-correlation analysis.

During the USI sequence selection and cross-correlation analysis the researcher was blinded to the participant (including their relevant demographic data), the recording session and the neural mobilisation exercise that was tested.

8.4.6 Frame-by-frame cross-correlation algorithm and calculation software.

Each video sequence was then analysed off-line using a method of frame-by-frame cross-correlation analysis that was developed in Matlab (Mathworks, USA) by Dilley et al. (Dilley et al., 2001). This method employs a cross-correlation algorithm to determine relative movement between successive frames in a sequence of ultrasound images (Dilley et al., 2001). During the analysis, the program compares the gray scale values of speckle features from the regions of interest (ROI's) within the nerve between

adjacent frames of the image sequence. In the compared frame, the coordinates of the ROI are offset along the horizontal and vertical image planes a pixel at a time within a predetermined range. A correlation coefficient is calculated for each individual pixel shift. The peak of a quadratic equation fitted to the maximum three correlation coefficients is equivalent to the pixel shift/movement between adjacent frames (Dilley et al., 2001). Pixel shift measurements for the nerve were offset against (subtracted from) pixel shifts measurements within the same USI field, from stationary structures (i.e. subcutaneous layers, bone, etc.). This method allows for any slight movement of the ultrasound transducer to be eliminated from the analysis. This method has proved to be a highly reliable method of assessment of nerve motion (Coppieters et al., 2009; Dilley et al., 2001; Ellis et al., 2008).

8.4.7 Synchronisation of data collection systems.

As data of the variables were able to occur at a collection rate divisible by three, synchronisation of data across the three second testing period was simplified (e.g. over the three second period 60° passive knee movement, 90 samples for cervical/knee ROM recording and 90 ultrasound frames). Although the cervical movement occurred over a three second period, this was an active movement which was performed by each individual participant. Therefore a set velocity of movement could not be utilised. However, each participant was instructed to complete the cervical movement over the three second period, and all participants had familiarisation trials to learn the timing required. The recording equipment (Fastrak and USI) were simultaneously initiated at the same time the Biodex initiated the joint movements. All data were captured onto a computer and then synchronised, off-line.

8.4.8 Statistical analysis.

To ensure standardisation between the three neural mobilisations, mean and range calculations were performed for cervical and knee ROM, recorded from the Fastrak system. Paired t-tests were used to calculate whether any differences were present for the total cervical and knee ROM recordings between each of the neural mobilisations exercises. For all tests, the alpha level was set was at 0.05.

The point of greatest sciatic nerve excursion was calculated by finding the maximum difference in excursion between each successive frame during the USI sequence and relating this to the corresponding time point across the three second testing period. Paired t-tests were used to calculate whether any differences were present for the time point where maximum sciatic nerve excursion occurred, between each of the neural mobilisations exercises. For all tests, the alpha level was set was at 0.05.

8.5 RESULTS

Descriptive statistics in respect to the amount of sciatic nerve excursion recorded with each neural mobilisation exercise are presented in Table 9. Relevant cervical, knee ROM and sciatic nerve excursion data were also determined at each quarter during the three second exercise performance (Table 10).

Table 9. Descriptive results for longitudinal sciatic nerve excursion across the neural mobilisation exercises

Neural Mobilisation	Mean nerve Excursion (mm)	Standard deviation (SD)	Standard error (SE)	95% Confidence interval for mean	
				Lower bound	Upper bound
TEKS	3.21	1.97	0.36	2.47	3.95
OEKS	2.63	1.44	0.26	2.09	3.17
KT	2.56	1.49	0.27	2.00	3.12

Abbreviations: TEKS, 2-ended knee slider; OEKS, 1-ended knee slider; KT: knee tensioner

Graphical representations of all data sets for each of the three neural mobilisation exercises are presented in Figures 21, 22 and 23. For each graph the dashed line represents the time where the maximum rate of sciatic nerve excursion occurred.

The TEKS and KT depicted a sigmoidal sequence of nerve excursion (Figures 21 and 23). The OEKS did not as there was no shoulder region evident (Figure 22). For the TEKS the maximum sciatic nerve excursion was 0.21mm after 73% of the exercise was completed (Figure 21), for the OEKS 0.17mm after 80% (Figure 22) and for the KT 0.17mm after 77% (Figure 23). Combined data sets for all three neural mobilisation exercises are presented in Figure 24.

The first point where a significant difference in nerve excursion between the TEKS and OEKS ($P<0.05$) occurred after 67% of the exercise was completed. After 90% of the exercise was completed, a significant difference in sciatic nerve excursion existed between the TEKS and KT ($P<0.05$). No significant difference in sciatic nerve excursion was seen between the OEKS and KT ($P>0.05$).

Table 10. Cervical, knee ROM and sciatic nerve excursion at each quarter during the three second exercise performance

Neural Mobilisation	Data	Quarters during neural mobilisation performance (% of movement time)			
		25%	**50%**	**75%**	**100%**
TEKS	Cervical ROM (°)	43.0	-11.0	-40.6	-53.8
	Knee ROM (°)	63.4	43.3	24.5	19.6
	Sciatic nerve excursion (mm)	0.12	0.80	2.09	3.21
OEKS	Cervical ROM (°)	27.2	27.2	26.5	28.0
	Knee ROM (°)	65.8	45.7	26.5	20.0
	Sciatic nerve excursion (mm)	0.06	0.62	1.67	2.63
KT	Cervical ROM (°)	4.3	56.5	87.7	93.1
	Knee ROM (°)	63.7	43.3	24.2	20.6
	Sciatic nerve excursion (mm)	0.09	0.74	1.71	2.56

Abbreviations: TEKS, 2-ended knee slider; OEKS, 1-ended knee slider; KT: knee tensioner; ROM: range of movement

In respect to the knee ROM utilised across the three neural mobilisations the mean±SD ROM was 58.0°±1.3° knee extension (from 78.5°±1.8° to 20.5°±0.1° flexion). There were no significant difference seen between the start and end positions for knee ROM across all three neural mobilisation ($P>0.3$). For the TEKS the mean range of cervical extension was 125.3°±17.5° extension (81.4°±21.7° flexion through to 43.9°±17.9° extension). For the KT the mean range of cervical flexion was 126.3°±23.3° (29.5°±21.3° extension through to 96.8°±21.7° flexion). There was no significant difference seen between the TEKS and KT for the full cervical ROM utilised ($P>0.8$). For the OEKS (where the cervical spine was stationary) the mean neutral cervical position was 27.3°±17.9° flexion.
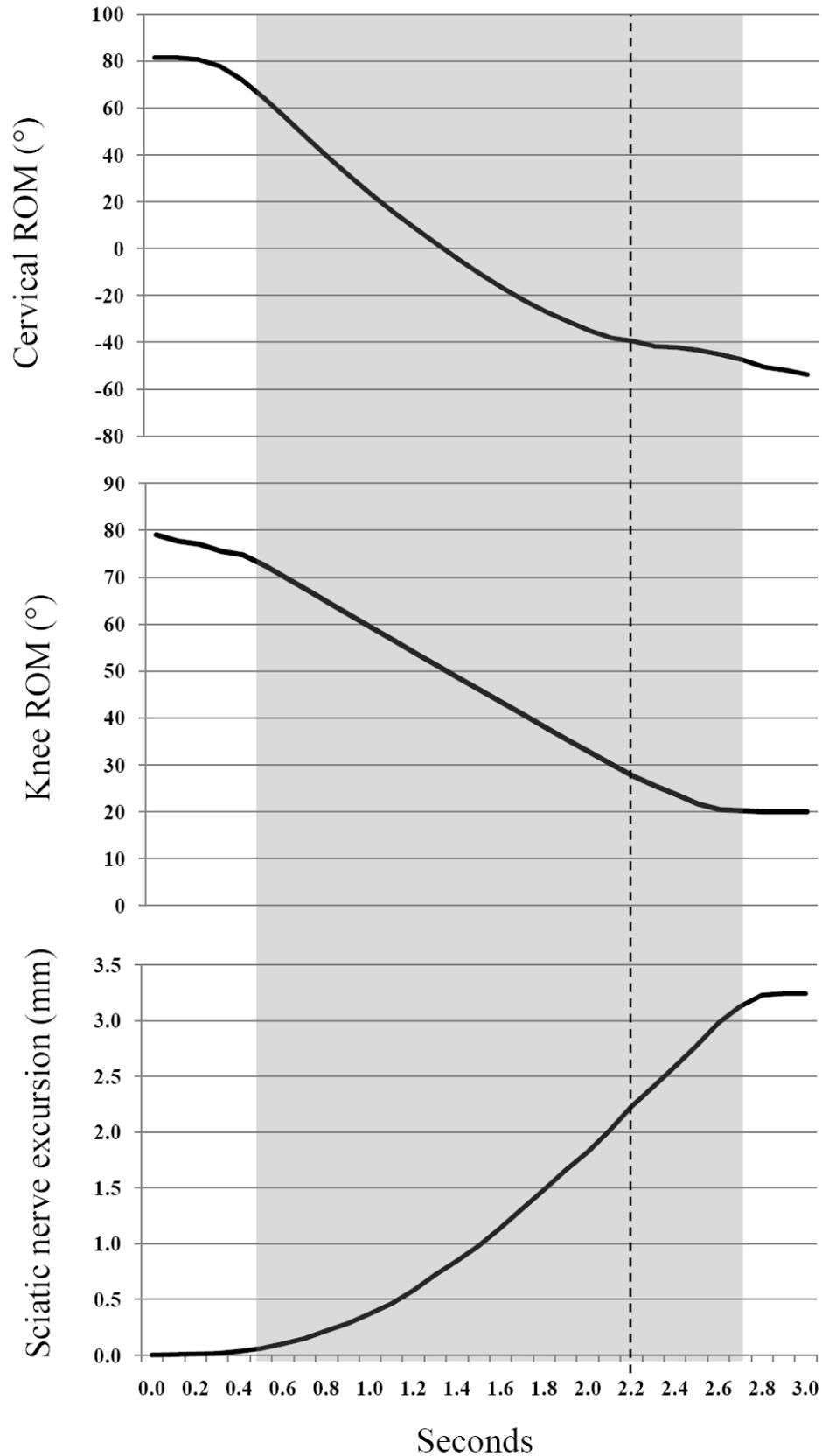
Figure 21. Relationship of sciatic nerve excursion, knee and cervical movement during TEKS. Positive value for cervical ROM = flexion, negative value = extension. Grey box represents period of constant Biodex velocity (knee joint). Dashed line represents time of peak nerve excursion (0.21mm at 2.2 seconds, 73% of the exercise was completed).
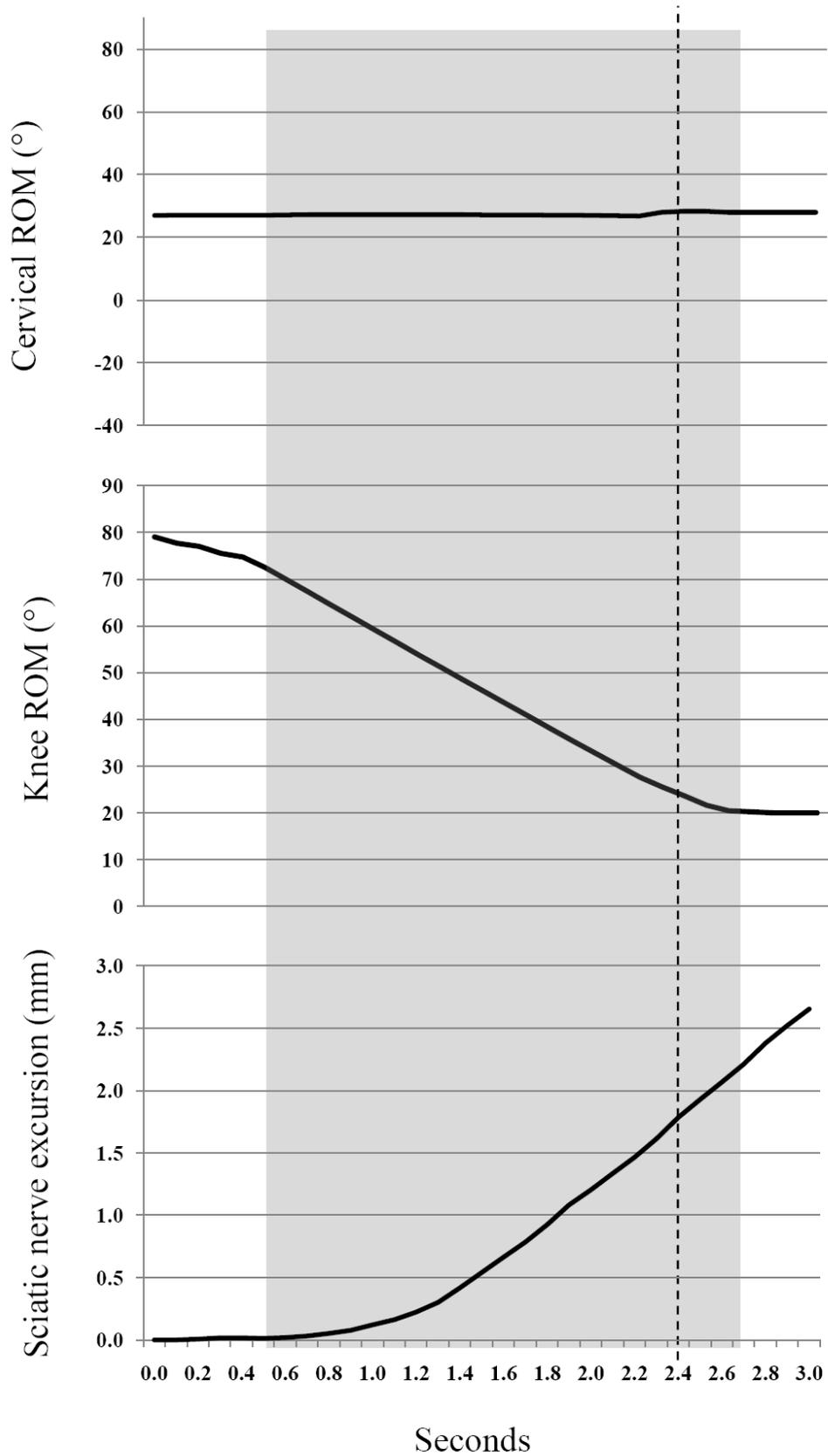
Figure 22. Relationship of sciatic nerve excursion, knee and cervical movement during OEKS. Positive value for cervical ROM = flexion, negative value = extension. Grey box represents period of constant Biodex velocity (knee joint). Dashed line represents time of peak nerve excursion (0.17mm at 2.4 seconds, 80% of the exercise was completed).
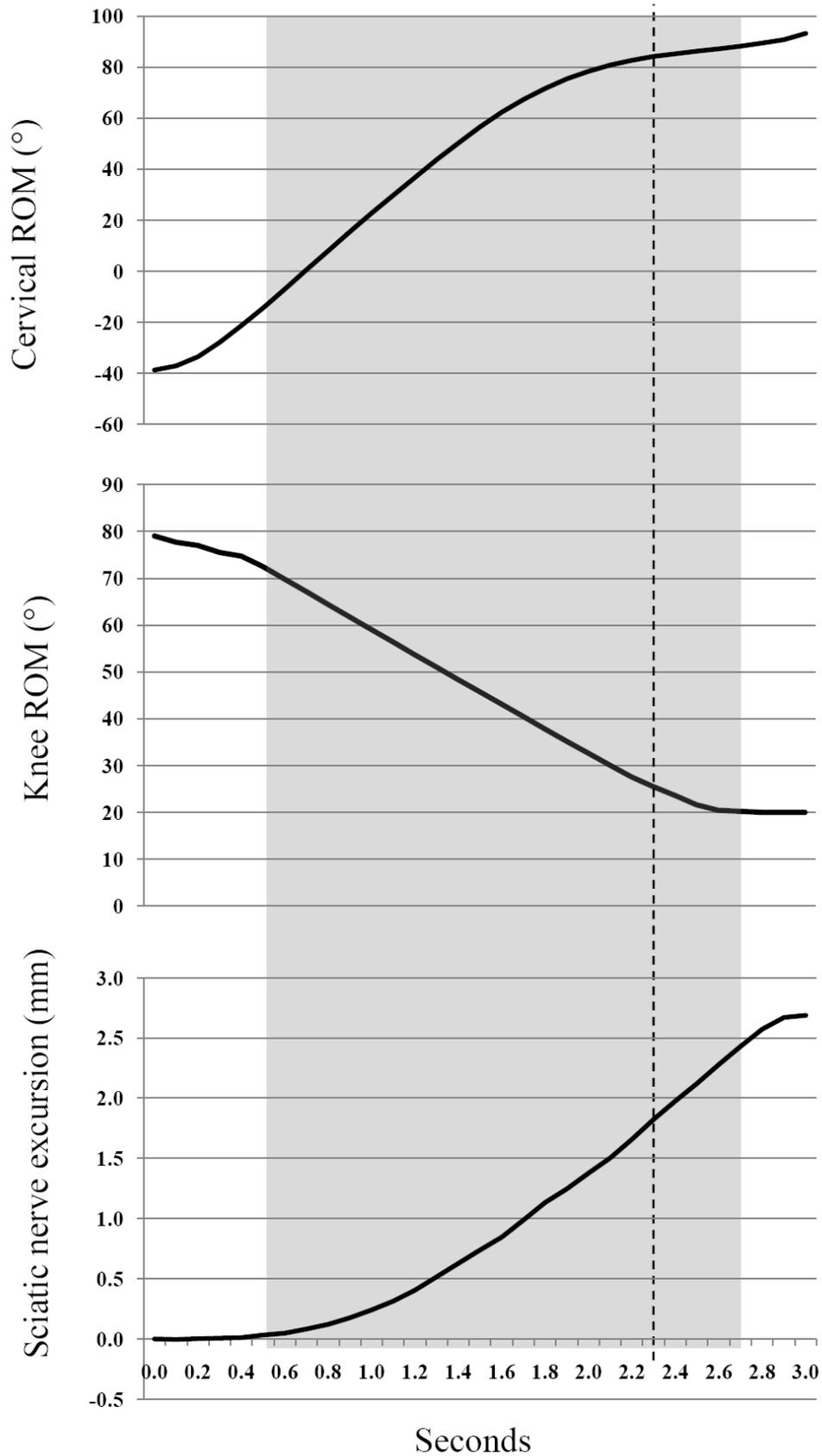
Figure 23. Relationship of sciatic nerve excursion, knee and cervical movement during KT. Positive value for cervical ROM = flexion, negative value = extension. Grey box represents period of constant Biodex velocity (knee joint). Dashed line represents time of peak nerve excursion (0.17mm at 2.3 seconds, 77% of the exercise was completed).
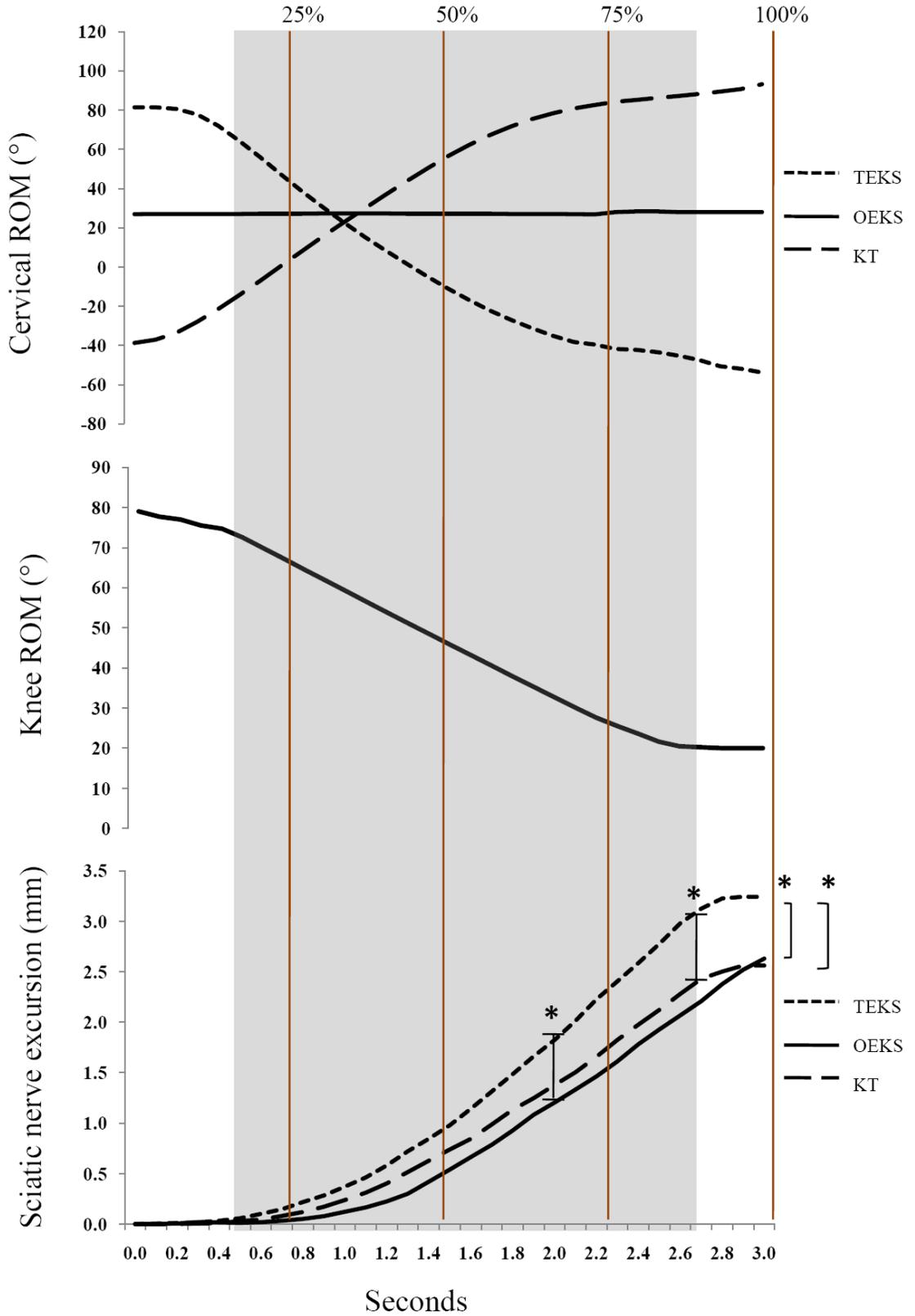
Figure 24. Sciatic nerve excursion, knee and cervical ROM data for all neural mobilisation exercises Positive value for cervical ROM = flexion, negative value = extension. Grey box represents period of constant Biodex velocity (knee joint). Vertical lines demarcate the percentage of the exercise complete (i.e. 25%, 50%, 75%, 100%). * = significant difference in sciatic nerve excursion (*P*<0.05). TEKS: 2-ended knee slider; OEKS: 1-ended knee slider; KT: knee tensioner

8.6 DISCUSSION

Although joint movement will result in the excursion and stretch of many different soft tissues, this study specifically examined excursion of the sciatic nerve. This was achieved by ensuring that the frame-by-frame cross-correlation software assessed pixel movement confined to the sciatic nerve and not that for the adjacent soft tissues. Subsequently, the results of this study demonstrate that there is a defined sequence of sciatic nerve excursion during neural mobilisation exercises. The primary hypothesis predicted that the plot of sciatic nerve excursion data would follow a sigmoidal pattern. A sigmoid curve is an *S* shaped curve that is distinguished by a gradual toe region followed by a steeper linear region and finishes with a flatter shoulder region. Theories suggest that nerves will exhibit a sequence of movement, in response to limb movement, with unfolding first followed by a period of excursion, excursion will then taper off and elongation will occur (Topp & Boyd, 2006). Two of the three exercises that were tested (TEKS and KT) demonstrated a sigmoidal sequence for excursion as predicted in the study hypothesis. Whilst the OEKS did demonstrate toe and linear regions no shoulder region was evident.

All three neural mobilisation exercises demonstrated a clearly defined toe region. The toe region represents a period of nerve unfolding (Julius et al., 2004). Upon completion of the first 25% of the exercise (at 0.75 seconds) sciatic nerve excursion was minimal (<0.13mm) with no statistically significant differences seen across the three exercises.

In using the Biodex dynamometer, a constant velocity of passive knee extension was maintained between 0.5 – 2.7 seconds for all three neural mobilisation exercises (see grey shaded area in Figures 21-24). As the toe regions for all three exercises

extended beyond 0.5 seconds it is apparent that this toe region was not solely due to acceleration of the Biodex.

The linear region represents the most significant period of nerve excursion. In this study the linear region extended into the last quarter of each of the exercises performance (between 75% - 100% completion). The first point where a significant difference in nerve excursion occurred was between the TEKS and OEKS at 2.0 seconds (upon completion of 67% of the exercise). Of note is the fact that the maximum rate of nerve excursion for each of the exercises occurred just after this point (TEKS 2.2 seconds, OEKS 2.4 seconds, KT 2.3 seconds).

The secondary hypothesis of this study was that the greatest rate of sciatic nerve excursion would occur during the middle half of the exercise performance (between 25% and 75% of the exercise being completed, 0.75 – 2.25 seconds). This hypothesis was only confirmed with the TEKS. However the greatest rate of nerve excursion for the OEKS and KT was very close to the mid-range of each exercise, just after 75% of the exercise had been completed.

The shoulder region of a sigmoid curve would suggest that nerve excursion is starting to reduce, as the movement progresses towards nerve elongation. A key factor was that during all three exercises passive knee movement began to decelerate as the Biodex reached the end of the set knee ROM. This deceleration could also give the nerve excursion curve an appearance of reduced excursion which may be mistaken for a shoulder region. However the OEKS did not demonstrate a shoulder region (Figure 22). This was the only exercise that relied solely on passive knee movement to generate nerve excursion. Had the deceleration of the passive knee movement been significant at the end of the period of constant knee velocity (2.7 seconds) then all three exercises would have exhibited a reduction of nerve excursion (i.e. a shoulder region). Therefore

the shoulder region exhibited during the TEKS and KT is due to nerve elongation rather than deceleration of the Biodex.

Effectively for the OEKS, upon completion of the exercise, nerve excursion remained within the linear region. Unlike the OEKS, the TEKS and KT demonstrated a shoulder region. However both the TEKS and KT utilised cervical movement as part of the neural mobilisation sequence whereas the cervical spine remained stationary during the OEKS. The direction of cervical movement may have influenced the excursion sequence directly. During the TEKS, cervical extension, in theory, would have lent more available length to the nerve tract which resulted in greater nerve excursion towards an elongation phase. Opposite to this, cervical flexion has the potential to increase general neural load, via the spinal cord and lumbosacral nerve roots, which would potentially result in a faster transition from a linear region into the shoulder region as elongation occurs.

Identification of a sequence of nerve excursion, during neural mobilisation exercises, may provide insight for future exercise design. As has previously been suggested, sliders allow more excursion with less tension, whereas tensioners offer less excursion with more tension (Coppieters & Alshami, 2007; Coppieters & Butler, 2008; Coppieters et al., 2009). Furthermore, an understanding of where or at what point during the range, of a particular exercise, excursion or elongation can be maximised could be useful for use clinical disorders where nerve excursion may be impaired.

The implication from this research is that maximal sciatic nerve excursion occurs during the mid-late range during a specific exercise. For example, during the TEKS sciatic nerve excursion was greatest as the knee extends to approximately ($\approx$) 25° flexion and the cervical spine extends to $\approx$41° extension. Performance of this type of neural mobilisation will not maximise sciatic nerve excursion at the PMT unless these

ranges of joint movement are met. Likewise if sciatic nerve elongation was desired then the choice of a KT would be logical and ideally would be performed with knee extension beyond ≈21° flexion and cervical flexion beyond ≈88°.

A limitation of this study is that passive knee movement did not continue towards terminal knee extension (0°). The deliberate intention of this study was to avoid the limits of knee extension in order to reduce any possible adverse effects of stretching the sciatic nerve and associated nerve tracts. Therefore any discussion regarding the sequence of nerve excursion can only be presented in respect to the three second testing period and the limited knee joint range that were used.

Although it was possible to create a standardised range and velocity of knee joint movement, the same could not be created for active cervical movement. The only standardising factor was the performance of cervical movement over the three second testing period, which presents another limiting factor.

8.7 CONCLUSION

It is apparent during neural mobilisation exercises that a specific sequence of nerve excursion occurs when the exercises utilised simultaneous joint movements at either end of the nerve bed. This sequence can be associated with specific biomechanical features of nerve movement such as unfolding, sliding and elongation. Sciatic nerve excursion is greatest towards the mid-late range of a neural mobilisation exercise performance. This information will be crucial in the specific design and prescription of neural mobilisation exercises to suit certain neural pathologies.

REFERENCES

The references for this paper have been included in the full reference list of this thesis.

Chapter Nine. Discussion and conclusions

Neural mobilisation is utilised to directly influence peripheral nerves in order to optimise nerve mechanics and nerve physiology. However the central issue remains that much of the discussion regarding neural mobilisation is based on theory. There is currently a lack of scientific evidence to support the clinical use of neural mobilisation and to validate the theoretical benefits that it offers (Di Fabio, 2001; Medina McKeon & Yancosek, 2008).

Furthermore, there is limited research evidence, certainly within *in-vivo* human populations, that documents the mechanical effects of neural mobilisation. The research that is available has focused upon the upper limb. There are no studies that have specifically assessed *in-vivo* nerve mechanics, during neural mobilisation, for the lower limb. Consequently this thesis has sought to address these issues, particularly in response to enhancing future design and prescription of neural mobilisation and to allow more accurate interpretation of their clinical value.

9.1 TOWARDS A BETTER UNDERSTANDING OF NEURAL MOBILISATION

Contemporary views regarding the use of neural mobilisation have tended to focus upon theoretical concepts of directly influencing nerve mechanics. Clinical importance is given to neural mobilisation as there is a belief that impaired peripheral nerve movement is a feature of a number of different peripheral neuropathies (Dilley et al., 2008; Erel et al., 2003; Greening et al., 2005; Greening et al., 2001; Greening et al.,

1999; Hough et al., 2007a; Nakamichi & Tachibana, 1995; Rozmaryn et al., 1998; Szabo et al., 1994; Wilgis & Murphy, 1986).

The difficulty exists in the lack of clinical trials that have directly assessed nerve mechanics during neural mobilisation. The research to date, that has examined neural mobilisation from a therapeutic perspective, has used measures of clinical improvement (i.e. pain scales, joint ROM, functional outcomes measures, neurodynamic testing, etc.) rather than outcome measures which directly assess nerve mechanics. This is problematic considering one of the primary aims of neural mobilisation is to enhance nerve movement.

The systematic review conducted as part of this thesis collated all RCTs that have examined the therapeutic benefit of neural mobilisation. One of the key findings of this review was the heterogeneity among outcomes measures and the lack of methodological rigour, which supported the views of a similar systematic review (Medina McKeon & Yancosek, 2008). Neural mobilisation exercises, symptom duration, lack of control group standardisation and differences in control group treatment have been identified as methodological inconsistencies in RCTs that were examined from the systematic review for this thesis.

Furthermore, none of the trials utilised an outcome measure that directly assessed nerve mechanics, of which the future assessment of neural mobilisation must include. However, in order to provide context for populations with nerve disorders, the assessment of nerve movement in healthy participants needs to be established first. This doctoral research has sought to achieve this by examining the influence of neural mobilisation on movement of the sciatic nerve.

9.2 ULTRASOUND ASSESSMENT OF SCIATIC NERVE EXCURSION

USI provides a significant opportunity to assess nerve motion. Its true advantage is that it provides the ability to assess nerve mechanics in real-time and *in-vivo* which most other imaging techniques do not (Chiou et al., 2003; Echigo et al., 2008; Hashimoto et al., 1999; Jeffery, 2003; Martinoli et al., 2000). Already there are many studies which have utilised USI to assess peripheral nerve motion (Coppieters et al., 2009; Dilley et al., 2003; Dilley et al., 2008; Dilley et al., 2007; Echigo et al., 2008; Ellis et al., 2008; Erel et al., 2003; Erel et al., 2010; Greening et al., 2005; Greening et al., 2001; Greening et al., 1999; Hough et al., 2000a, 2000b, 2007a; Julius et al., 2004). However, there are only a few published studies, to date, which have used USI to assess nerve movement (median nerve) during neural mobilisation (Coppieters et al., 2009; Echigo et al., 2008).

From a research perspective, it is vital that USI is a reliable and a valid tool for assessing nerve motion. Already several studies have concluded excellent reliability in the assessment of median nerve movement using USI utilising either speckle tracking (Coppieters et al., 2009; Dilley et al., 2001) or Doppler ultrasound (Hough et al., 2000b) to calculate movement.

The initial two studies of this thesis (Chapters Four and Five) utilised USI and frame-by-frame cross-correlation software to assess sciatic nerve excursion, during neural mobilisation exercises, and concluded excellent reliability at the PMT. These findings were consistent with the findings of previous research which has used similar methods (Coppieters et al., 2009; Dilley et al., 2001). This doctoral research is the first to assess the reliability of measuring sciatic nerve movement *in-vivo* during neural mobilisation. It is also one of the first to attempt to quantify *in-vivo* movement of any of the lower limb peripheral nerves.

From the findings of this thesis, in agreement with Hough et al. (2000b), USI analysis provides a reliable research tool to quantify nerve movement during therapeutic techniques which are designed and utilised to deliberately manipulate and exploit nerve movement. As further research, using USI, examines *in-vivo* nerve mechanics, the underlying premise that neural mobilisation can influence nerve movement can be scrutinised. Furthermore, an initial focus within healthy populations can be taken forwards into clinical populations.

9.3 SCIATIC NERVE EXCURSION IN RESPECT TO DIFFERENT TYPES OF NEURAL MOBILISATION

The contemporary use of neural mobilisation has seen the development of different types of exercises. Several studies have been conducted which have assessed the difference in nerve mechanics between different exercises: sliding techniques and tensioning techniques (Coppieters & Alshami, 2007; Coppieters & Butler, 2008; Coppieters et al., 2009). The general conclusions from these studies were that sliders resulted in greater amounts of nerve excursion compared to tensioners. Sliders initiated simultaneously at two ends (i.e. two-ended sliders) generally resulted in greater nerve excursion compared to those initiated at one end only (i.e. one-ended sliders). Cadaveric studies (Coppieters & Alshami, 2007; Coppieters & Butler, 2008) have also concluded a relationship between nerve excursion and tension, with tensioners resulting in greater nerve tension but less nerve excursion compared to sliders.

The study that examined sciatic nerve excursion between different neural mobilisation exercises, conducted as part of this thesis, revealed findings in agreement with those of Coppieters et al. (2009). For example, the two-ended slider, involving simultaneous knee extension and cervical extension performed in slump-sitting (TEKS)

resulted in significantly more sciatic nerve excursion (3.21mm) compared to the tensioner (KT) (2.56mm) (*P*<0.02). Furthermore, the two-ended slider resulted in significantly more sciatic nerve excursion (3.21mm) compared to the one-ended slider (2.63mm, involving only knee extension) (*P*<0.02).

From the studies mentioned above, there is a consistent pattern that a two-ended slider will result in the greatest amount of nerve excursion. It has been postulated that a cumulative effect is created during a two-ended slider. As tension is taken up in one end of the nerve bed, tension is being released at the other resulting in greater nerve excursion (Coppieters et al., 2009).

The joint movements utilised in this doctoral research were generated at the knee and cervical spine. It is interesting to note that cervical extension, in combination with knee extension, resulted in a cumulative effect as seen with significantly greater nerve excursion from the two-ended compared to the one-ended technique. However, cervical flexion (CF) on its own did not result in significant sciatic nerve excursion (-0.09 ± 0.13mm, a negative value indicating a proximal movement). Furthermore no significant difference was seen between the one-ended knee slider (OEKS) and the tensioner (KT) (the only difference between the two exercises from adding cervical flexion to become the tensioner) (*P*=0.70).

Cervical flexion has been shown in research involving cadavers to cause cranial movement of lumbar and thoracic spinal nerve roots (Breig, 1978; Breig & Marions, 1963), up to 3 - 4mm of movement at the thoracic nerve roots (Breig & Marions, 1963). Although theories suggest that the entire nervous system is continuous, it is generally accepted that, in spite of nerve movement being greatest closer to the axis of joint rotation, nerve excursion becomes less the further away movement is occurring from the

joint (Coppieters et al., 2006; Echigo et al., 2008; Ellis et al., 2008; Hall et al., 1998; Shacklock, 2005a).

It is likely that the reason behind minimal sciatic nerve excursion seen on cervical flexion alone, and the non-significant difference observed between the one-ended slider and the tensioner, is that the cervical spine is distant to the scanning location (PMT). Neural compliance throughout the nervous system between these two locations was enough to accommodate neural tissue unfolding only without a great degree of excursion witnessed.

It is worth considering, therefore, whether the use of cervical movement is the best choice for maximising sciatic nerve excursion, at the level of the PMT, during slump-sitting based neural mobilisation exercises. From this research it would be worthwhile examining the effect of using joint motion that is closer to the region of interest, for example movement at the lumbar spine or hips.

9.4 THE BIOMECHANICS OF SCIATIC NERVE EXCURSION DURING NEURAL MOBILISATION

An understanding that different neural mobilisation exercises will result in different amounts of nerve excursion is certainly useful, from a clinical perspective, in order to choose the framework for the choice of a particular mobilisation to utilise. However, there is more information that must be incorporated into a deeper construction of neural mobilisation.

9.4.1 The relevance of the continual system.

The fact that the nervous system is a continuum is a crucial fact (Breig, 1978; Butler, 2000; Gifford, 1998; Lew et al., 1994; Shacklock, 2005a, 2007; Walsh, 2005). Essentially tension that is imposed upon the nervous system will have a local effect on excursion and physiology, but it will also have distant effects upon the continual system, albeit less in magnitude (Dilley et al., 2003; Dilley et al., 2008; Echigo et al., 2008; Ellis et al., 2008; Julius et al., 2004; Reid, 1960; Wright et al., 2001).

As has been shown in this thesis, significantly greater sciatic nerve excursion, in all directions assessed (transverse and longitudinal), was observed at the popliteal crease compared to the PMT from excursion being induced by passive ankle dorsiflexion during a two-ended slider in sitting (see Chapter Four). Evidence of the same phenomenon occurred when using a fixed scanning location, the PMT, which resulted in significantly greater sciatic nerve excursion seen from extending the knee compared to passive dorsiflexion of the ankle, once again with a two-ended slider in sitting (see Chapter Six). Sciatic nerve excursion also reduced significantly when greater tension was added, during a side-lying neural mobilisation, from progressively extending the knee (see Chapter Five).

In order to decrease the possible summation of excessive mechanical force in response to elongation of the nerve bed (Butler, 1989, 2000; Shacklock, 2005a), peripheral nerves dissipate load by moving along a pressure gradient towards the axis of movement (Phillips et al., 2004; Shacklock, 1995b, 2005a; Topp & Boyd, 2006). The findings of this thesis certainly support this premise with sciatic nerve movement consistently towards the moving joint. This is in line with previous research, conducted within cadaver models (Coppieters et al., 2006; Goddard & Reid, 1965; Reid, 1960;

Smith, 1956) and *in-vivo* in the upper limb (Coppieters et al., 2006; Goddard & Reid, 1965; Reid, 1960; Smith, 1956).

9.4.2 The effect of increased neural tension.

There is an inversely proportional relationship between nerve strain and excursion in that increased nerve tension will result in decreased nerve excursion (Coppieters & Alshami, 2007; Coppieters & Butler, 2008). Following this doctoral research this aforementioned phenomenon was evident. For example, a two-ended slider (which has been shown in cadaver research to cause significantly less nerve strain than other neural mobilisation exercises) (Coppieters & Alshami, 2007; Coppieters & Butler, 2008) resulted in significantly less sciatic nerve excursion compared to a tensioner (3.21mm compared to 2.56mm) (Chapter Six).

However upon closer inspection of the components used in the slump-sitting neural mobilisations, it seems that the use of cervical flexion, to add further load to the system, did not consistently result in a decrease of sciatic nerve excursion. The addition of cervical flexion to a one-ended slider, induced with ankle dorsiflexion, resulted in a significant decrease in sciatic nerve excursion (at the level of the PMT). However, the decrease in sciatic nerve excursion seen from adding cervical flexion, to a one-ended slider induced with knee extension, was not significant (Chapter Seven).

There is evidence to suggest that cervical flexion can add tension generally to the spinal cord and associated nerve roots as it is considered an important aspect of the slump test. There are reports in cadaver research that cervical flexion can result in cranial excursion of the lumbo-sacral nerve roots (Breig, 1978; Breig & Marions, 1963; Breig & Troup, 1979b). *In-vivo* studies have recorded a reduction in knee extension

when cervical flexion is added to a slump test (Fidel et al., 1996; Herrington et al., 2008; Johnson & Chiarello, 1997; Tucker et al., 2007; Yeung et al., 1997).

However, certainly for movement induced at the knee in slump-sitting, it was not seen in this research that the addition of cervical flexion resulted in a significant decrease in sciatic nerve excursion. It is possible that the knee ROM that was utilised (60° of knee extension) was not sufficient to cause elongation of the sciatic nerve tract thereby reducing nerve excursion. It also needs to be considered that for more proximal aspects of the sciatic nerve tract, excursion is likely to be more evident closer to the sacral plexus and spinal nerve roots. It is a limitation of this research that nerve excursion measurement, using USI, was not extended to this level.

In order to more clearly understand the relevance of general neural tension imposed during slump-sitting neural mobilisation exercises, similar research needs to be conducted comparing the amount of sciatic nerve excursion during exercises performed in slump-sitting compared to upright sitting. From the pilot results of seven participants (unpublished data from this doctoral research), who were assessed for sciatic nerve excursion at the PMT, there was greater sciatic nerve excursion during both a two-ended knee slider and one-ended knee slider performed in upright sitting as opposed to slump-sitting (two-ended slider $P=0.37$, one-ended slider $P=0.01$; paired t-tests, $\alpha<0.05$). The mixed results of this pilot trial are encouraging enough to expand this analysis across a wider population to further examine the influence of slump and general neural tension.

9.4.3 Exploiting the sequence of nerve excursion.

The analysis of sciatic nerve excursion at the PMT, in response to different neural mobilisation exercises, demonstrated a sigmoidal pattern for two of the three neural mobilisations that were examined (the two-ended knee slider (TEKS) and knee tensioner (KT)). A defined toe-region (indicative of unfolding) followed by a linear region (indicative of excursion) followed by a shoulder region (indicative of elongation) was evident following the analysis of nerve excursion. The one-ended knee slider (OEKS) exhibited a toe-region and a liner region, but did not exhibit a shoulder region (see Chapter Eight). Although there has been clinical commentary in regard to a sequence of nerve excursion (Topp & Boyd, 2006), this doctoral research is the first to identify a sequence of nerve excursion during neural mobilisation. What has been seen following this research supports the theories that have already been presented by Topp and Boyd (2006).

From a clinical perspective, understanding this sequence of nerve excursion is crucial for the optimal design of neural mobilisation exercises. For example, if nerve excursion is to be targeted for a condition where excursion is perceived to be impaired, then the range of joint movement that is used must include the linear region to maximise nerve excursion.

From the assessment of the two-ended knee slider and knee tensioner, the linear region occurred from 0.75 – 2.7 seconds over a 3 second testing period. In other words the maximum sciatic nerve excursion occurred during the mid-outer range of motion during these two neural mobilisations (at approximately 25° knee flexion, 0° is equivalent to terminal knee extension). Furthermore, to exploit the shoulder-region, neural mobilisation exercises need to use outer range joint movements to lengthen the

nerve bed for genuine elongation or stretching to occur (beyond 21° of knee flexion towards terminal knee extension) (see Chapter Eight).

9.5 CLINICAL IMPLICATIONS

The identification of the underlying pathogenesis of peripheral nerve disorders may also improve the selection of neural mobilisation techniques (Medina McKeon & Yancosek, 2008; Muller et al., 2004). For example, if impaired nerve excursion is suspected, then selection of neural mobilisation exercises, such as sliders, to maximise nerve excursion would be justified (Coppieters et al., 2009; Medina McKeon & Yancosek, 2008). In order to assess the potential changes in nerve excursion that may occur from using neural mobilisation, it is imperative that reliable tools for of assessing nerve excursion (i.e. USI) are utilised as primary outcome measures. However the key problem exists that there is still a lack of concrete evidence that a loss of nerve excursion is a primary causative factor in many peripheral nerve disorders.

Concern has been raised in regard to the design of neural mobilisation exercises and protocols (particularly those used post-operatively) when there is still a lack of clear understanding regarding nerve biomechanics (Szabo et al., 1994). The relationship between nerve strain and nerve excursion must be carefully and judiciously balanced when designing and prescribing neural mobilisation exercises.

The findings of this doctoral research suggest that sliders will result in greater nerve sciatic nerve excursion compared to tensioners. This supports similar research conducted in the upper limb (Coppieters et al., 2009). This finding needs to be kept in context that sliders have also been shown to result in a reduction in nerve strain and vice versa for tensioners (Coppieters & Alshami, 2007; Coppieters & Butler, 2008). This

doctoral research also concluded that a two-ended slider resulted in greater nerve excursion compared to one-ended sliders, nerve excursion was greatest closest to the axis of joint movement and that nerve excursion exhibited a sigmoidal sequence.

Therefore to maximise nerve excursion, large amplitude movements in the mid-outer ranges of joint movement will be useful. Alternatively, to maximise nerve elongation, large to short amplitude movements towards the outer ranges will be required. Based on these findings, several recommendations for the design and use of neural mobilisation are offered:

It must also be noted, however, that currently there is controvesy regarding the presence of impaired nerve movement in many pathological conditions. Although it is appropriate to discuss clinical implications within this thesis, this discussion must be taken within the context that this research was conducted in normal, healthy populations and may change when more evidence is available regarding abnormal nerve mechanics.

9.5.1 Recommendations for the prescription of sliders.

Based upon previous research and the findings of the studies conducted within this thesis, the recommendations for designing a neural mobilisation to maximise nerve excursion at a local site, include:

- Choose a two-ended slider.
- Utilise joint movements that will lengthen the nerve bed, closest to the local site of dysfunction (as guided by clinical irritability).
- Utilise large amplitude joint movements within mid-outer range.

- Reduce excessive pre-load on the nervous system from the adopted exercise position, for example perform seated sliders in upright sitting, as opposed to slump-sitting.

9.5.2 Recommendations for the prescription of tensioners.

Based upon previous research and the findings of the studies conducted within this thesis, the recommendations for designing a neural mobilisation to encourage nerve elongation and stretch, include:

- Choose a tensioner.
- Utilise joint movements that will lengthen the nerve bed, closest to the local site of dysfunction (as guided by clinical irritability).
- Utilise large amplitude joint movements towards the outer range.
- Add pre-load on the nervous system from the adopted exercise position, for example perform seated sliders in slump-sitting, as opposed to upright sitting.

9.6 STUDY LIMITATIONS

- A limitation of all imaging studies that utilise USI occurs when the target tissue, in this study the sciatic nerve, moves beyond the viewing field of the ultrasound transducer (Hough et al., 2000a, 2007a). On the occasions where this occurred, either images were unable to be used or participants excluded. However this research limitation is by no means isolated to this study, in fact to most studies utilising USI to assess tissue motion.
- This research is limited to the findings of nerve excursion at the level of the posterior mid-thigh and popliteal fossa. Excursion of more proximal aspects of

the sciatic nerve and related nerve tract (including the sacral plexus and spinal nerve roots) was not conducted.

- For the final studies which utilised the Biodex to perform passive lower limb movement, a deliberate decision was made to limit both ankle and knee passive movement. As slump-sitting positions increase general load on the nervous system (Fidel et al., 1996; Slater et al., 1994), to avoid potential adverse effects of excessive increases in neural tension, the Biodex dynamometer was set to ranges below that of maximum knee and ankle joint movement. Clinically it would be common practice to use a range of joint movement, during a neural mobilisation exercise, up to or just prior to a level which would induce clinical symptoms (Shacklock, 2005a). The exercises used in this study did not attempt to do this and so must be viewed in context.

9.7 FUTURE RESEARCH FOR THE DEVELOPMENT OF NEURAL MOBILISATION

- The systematic review of RCTs which have assessed neural mobilisation, conducted as part of this thesis, highlighted the following methodological weaknesses: lack of (or lack of reporting) random allocation, concealed allocation, intention to treat analysis for participant drop-outs and inadequate blinding. Future RCTs designed to assess the therapeutic efficacy of neural mobilisation should strive to address these weaknesses.
- This doctoral research represents the first studies to examine the effect of neural mobilisation upon nerves of the lower limb. The systematic review conducted for this thesis also highlighted a lack of RCTs which have assessed neural

mobilisation in the treatment of peripheral nerve disorders of the lower quadrant and lower limb. Future research must explore these gaps.

- To date there is limited evidence that many peripheral nerve disorders truly involve a loss or impairment of nerve movement (i.e. loss of glide and slide, or inability to be able to elongate). There are only a few studies which have examined this issue in regard to CTS (Erel et al., 2003; Erel et al., 2010; Greening et al., 1999; Hough et al., 2007a), whiplash (Greening et al., 2005), NSAP (Dilley et al., 2008; Greening et al., 2005; Greening et al., 2001) and lumbar IVD herniation (Kobayashi et al., 2003). The use of dynamic imaging, like USI, should be a research tool that is utilised to establish whether loss or impairment of nerve movement is indeed a feature, particularly in light of the underlying premise of neural mobilisation to mechanically influence peripheral nerves and the relevant interface.

- The outcome measures which are used to measure treatment effect need to reflect as many of the perceived benefits that neural mobilisation may have. As has been discussed, neural mobilisation may have biomechanical, neurophysiological, and morphological benefits for the peripheral nervous system. Therefore standard clinical outcome measures (i.e. pain scales, functional outcome measures and neurodynamic tests) need to be matched with measures of nerve mechanics (i.e. nerve excursion measurement with USI), neurophysiological measures (i.e. oedema, blood flow, nerve conductance, etc.) and central effects (i.e. pain-pressure threshold testing, thermal sensitivity, etc.). In doing so neural mobilisation can be judged in accordance with the potential clinical, mechanical, neurophysiological, and central effects which they may possess.

- Two-dimensional (2D) USI was utilised in this research. Like all studies using 2D USI, the limitation exists that this method does not allow analysis of simultaneous movement within multiple planes. The movement of peripheral nerves and their surrounding interface occurs in multiple planes and it would be ideal to be able to assess nerve mechanics in multiple planes. Deng et al. (2000) suggests that the use of three (3D) and four-dimensional (4D) USI may provide the opportunity to measure real-time soft-tissue movement, including nerves, in multiple planes (Deng et al., 2000). More sophisticated USI technologies, such as i.e. 3D/4D imaging and sonoelastography, have been utilised successfully to determine *in-vivo* measures for volumetric changes in muscle (Barber, Barrett, & Lichtwark, 2009; Weller et al., 2007) and stress/strain changes in muscle, tendon and vessel walls (Duenwald, Kobayashi, Frisch, Lakes, & Vanderby, 2011; Klauser & Peetrons, 2010). Cadaver studies have established a relationship between nerve strain and excursion during neural mobilisation (Coppieters & Alshami, 2007; Coppieters & Butler, 2008). It would be significant progress to be able to determine whether the same relationship exists *in-vivo* by utilising new USI technologies (i.e. 3D/4D imaging and sonoelastography).

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Appendices

APPENDIX 1

Participant Information Sheet

Date Information Sheet Produced:

1st September, 2005

Project Title
The reliability of diagnostic ultrasound assessment of sciatic nerve movement during neural mobilisation.

Invitation
You are invited to take part in a research study performed as part of the requirements for completion of a Masters thesis. Information from this research will be presented within a written thesis (as per the requirements of a Masters of Health Science) and may also be presented within academic publications or verbal presentations.
Participation is completely voluntary and you may withdraw from the study at anytime without giving a reason or being disadvantaged.

What is the purpose of this research?
To establish the accuracy of measuring sciatic nerve movement during therapeutic nerve exercises using Diagnostic Ultrasound.

How are people chosen to be asked to be part of this research?
People with 'normal' sciatic nerve function will be asked to volunteer to take part in the study. If you have a history of lumbar spine or pelvic problems or upper leg or spinal surgery, please do not volunteer.

What happens in this research?
You will be asked to sit on a seat with your leg comfortably supported on a frame. An image of your sciatic nerve (through the hamstring muscles) using Diagnostic Ultrasound is taken. Images will be taken during a sequence of gentle leg and neck movements. The probe of the machine will be applied to the skin surface with transmission gel and moved around until a clear image is achieved. The image will show on a monitor from which recordings and calculations can be made. Prior to imaging, a mark will be drawn onto your skin, on the back of your thigh and your knee. These will be used as a reference marker.

What are the discomforts and risks?
There are no risks or discomfort from the ultrasound scanning. The transmission gel is water-based thus precluding an allergic reaction. The researcher will assist you with the gentle leg and neck movements and these will be performed without discomfort.

What are the benefits?
The benefit of performing this research is validation of a valuable tool which will provide the basis for future research. Diagnostic Ultrasound can be used over a broad range of pathologies in a number of clinical settings. Ultimately this will lead to an improvement in the quality of care delivered to the public through better diagnosis, recovery monitoring, biofeedback and improved treatments.

What compensation is available for injury or negligence?
Compensation is available through the Accident Compensation Corporation (ACC) within its normal limitations.

How will my privacy be protected?
Your privacy will be protected by identifying you only by a number. Access to the data is restricted to the researchers.

What are the costs of participating in this research?
There is no monetary cost. It will however cost approximately 30 minutes of your time in total.

What opportunity do I have to consider this invitation?
Before volunteering, please consider carefully whether you are prepared to be part of the study. There will some flexibility around the appointment times for the data collection. Please communicate clearly with us so convenience is optimised for all concerned, and appointments run smoothly and are on time.

How do I agree to participate in this research?
You will need to read and sign a Consent Form in order to participate in this study. A consent form can be obtained from either of the researchers (see contact details below). Please contact the researchers if you wish to join this study. You will be contacted prior to the start of data collection which is scheduled for October, 2006. This may be slightly earlier or later depending on how the set up of the study progresses.

Will I receive feedback on the results of this research?
Results will be made available to you at the completion of the study, and will be in the form of a written summary. If you wish to receive this, please indicate on the relevant section of the consent form. Any papers that may be published arising from the research can be accessed on request.

What do I do if I have concerns about this research?
If you have any concerns regarding the nature of this project then you should contact the Project Supervisor, Dr Wayne Hing, 921-9999 ext 7800.
Any concerns regarding the conduct of the research should be made to the Executive Secretary, AUTEC, Madeline Banda, madeline.banda@aut.ac.nz , 921 9999 ext 8044.

Who do I contact for further information about this research?
Researcher contact details:
Richard Ellis, work phone: 921-9999 ext 7090, ellisnz@yahoo.com

Project Supervisor Contact Details
Dr Wayne Hing, work phone: 921-9999 ext 7800

Approved by the Auckland University of Technology Ethics Committee on 10th October, 2005. AUTEC Reference number 05/186.

APPENDIX 2

Consent to Participation in Research

Title of Project: The reliability of diagnostic ultrasound
assessment of sciatic nerve movement during neural mobilisation.

Project Supervisor: Dr. Wayne Hing
Researcher: Richard Ellis

I have read and understood the information provided about this
research project (Information Sheet dated 1st September, 2005.).

I verify that I do not meet any of the Exclusion Criteria detailed in the Information
Sheet (namely if you have a history of lumbar spine or pelvic problems or upper leg or
spinal surgery, please do not volunteer).

I have had an opportunity to ask questions and to have them answered.

I understand that I may withdraw myself or any information that I have provided for this
project at any time prior to completion of data collection, without being disadvantaged
in any way.

I agree to take part in this research.

I wish to receive a copy of the report from the research: tick one: Yes   O   No   O

Participant signature: ....………………….....

Participant name: ……………………………………………………………….

Participant Contact Details (if appropriate):

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Date:

Approved by the Auckland University of Technology Ethics Committee on 17th
October, 2005. AUTEC Reference number 05/186

Note: The Participant should retain a copy of this form.

APPENDIX 3

UNIVERSITY
TE WĀNANGA ARONUI O TAMAKI MAKAU RAU

MEMORANDUM

To: Wayne Hing
From: **Madeline Banda** Executive Secretary, AUTEC
Date: 2 November 2005
Subject: Ethics Application Number 05/186 **The reliability of diagnostic ultrasound assessment of longitudinal sciatic nerve movement during neural mobilisation.**

Dear Wayne

Thank you for providing written evidence as requested. I am pleased to advise that it satisfies the points raised by the Auckland University of Technology Ethics Committee (AUTEC) at their meeting on 10 October 2005. Your ethics application is now approved for a period of three years until 2 November 2008.

I advise that as part of the ethics approval process, you are required to submit to AUTEC the following:

- A brief annual progress report indicating compliance with the ethical approval given using form EA2, which is available online through *http://www.aut.ac.nz/research/ethics*, including a request for extension of the approval if the project will not be completed by the above expiry date;

- A brief report on the status of the project using form EA3, which is available online through *http://www.aut.ac.nz/research/ethics*.   This report is to be submitted either when the approval expires on 2 November 2008 or on completion of the project, whichever comes sooner;

You are reminded that, as applicant, you are responsible for ensuring that any research undertaken under this approval is carried out within the parameters approved for your application. Any change to the research outside the parameters of this approval must be submitted to AUTEC for approval before that change is implemented.

Please note that AUTEC grants ethical approval only. If you require management approval from an institution or organisation for your research, then you will need to make the arrangements necessary to obtain this.

To enable us to provide you with efficient service, we ask that you use the application number and study title in all written and verbal correspondence with us. Should you

have any further enquiries regarding this matter, you are welcome to contact Charles Grinter, Ethics Coordinator, by email at charles.grinter@aut.ac.nz or by telephone on 921 9999 at extension 8860.

On behalf of the Committee and myself, I wish you success with your research and look forward to reading about it in your reports.

Yours sincerely

Madeline Banda
Executive Secretary
Auckland University of Technology Ethics Committee

Cc: Richard Francis Ellis ellisnz@yahoo.com

APPENDIX 4

Participant Information Sheet

Date Information Sheet Produced: **21st November, 2007**

Project Title
Can measurement of peripheral nerve movement strengthen and support the clinical findings of neurodynamic tests?

Invitation
You are invited to take part in a research study performed as part of the requirements for completion of a Doctoral (PhD) thesis. Information from this research will be presented within a written thesis (as per the requirements of a Doctor of Philosophy programme) and may also be presented within academic publications or verbal presentations. Participation is completely voluntary and you may withdraw from the study at anytime without giving a reason or being disadvantaged.

What is the purpose of this research?
To establish the accuracy of measuring sciatic nerve movement during therapeutic nerve exercises using Diagnostic Ultrasound.

How are people chosen to be asked to be part of this research?
People with sciatic nerve (the main nerve in the upper leg) dysfunction will be asked to volunteer to take part in the study. Sciatic nerve dysfunction refers to any symptoms which may arise from irritation of the sciatic nerve (i.e. low back, buttock, thigh pain; pins-and-needles; numbness etc). If you have a history of major trauma or surgery to the lumbar spine, pelvic or upper leg, please do not volunteer.   It is intended to recruit between 20-25 participants.

What happens in this research?
You will be asked to sit on a seat with your leg comfortably supported on a frame. An image of your sciatic nerve (through the hamstring muscles) using Diagnostic Ultrasound is taken. Images will be taken during a sequence of gentle leg and neck movements.   The probe of the machine will be applied to the skin surface with transmission gel and moved around until a clear image is achieved. The image will show on a monitor from which recordings and calculations can be made.
Prior to imaging, a mark will be drawn onto your skin, on the back of your thigh and your calf. These will be used as a reference marker.
You will be required to attend 1 visit which will last approximately 1 hour.

Where will the research take place?
Health and Rehabilitation Research Centre, AUT University, North Shore Campus, Akoranga Drive, Northcote.

What are the discomforts and risks?

The leg and neck movements are designed to reproduce the symptoms that you are experiencing. To limit your discomfort, you will only be asked to perform these movements until and stop at the very first symptom onset. Also, you will not be asked to hold any uncomfortable positions.

There are no risks or discomfort from the ultrasound scanning. The transmission gel is water-based thus precluding an allergic reaction. The researcher will assist you with the gentle leg and neck movements and these will be performed without discomfort.

What are the benefits?

The benefit of performing this research is to confirm a potential link and correlation between clinical tests and ultrasound imaging designed to highlight sciatic nerve dysfunction. Ultimately this will lead to an improvement in the quality of care delivered to the public through better diagnosis, recovery monitoring, biofeedback and improved treatments.

What compensation is available for injury or negligence?

Any harm caused to you by participation in this study may be covered by the Accident Rehabilitation and Compensation Insurance Act 1992. If it is determined that the reaction or event is likely to have been caused by participation in the research study, your GP will initiate the claims process, and assist you to complete the necessary paperwork to submit an ACC claim should you choose to do so. As with all claims to ACC, acceptance of your claim is not guaranteed and is subject to normal ACC claims assessment processes.

How will my privacy be protected?

Your privacy will be protected by identifying you only by a number. Access to the data is restricted to the researchers. No material which could personally identify you will be used in any reports on this study.

What are the costs of participating in this research?

There is no monetary cost. It will however cost approximately 60 minutes of your time in total.

What opportunity do I have to consider this invitation?

Before volunteering, please consider carefully whether you are prepared to be part of the study. There will some flexibility around the appointment times for the data collection. Please communicate clearly with us so convenience is optimised for all concerned, and appointments run smoothly and are on time.

Your participation is entirely voluntary. You do not have to take part in this study, and if you choose not to take part this will not effect any future care or treatment. If you decide to take part in this study, you will be free to withdraw at any stage.

How do I agree to participate in this research?

You will need to read and sign a Consent Form in order to participate in this study. A consent form can be obtained from either of the researchers (see contact details below). Please contact the researchers if you wish to join this study. You will be contacted prior to the start of data collection which will take place soon after you have indicated your availability.

Will I receive feedback on the results of this research?
Results will be made available to you at the completion of the study, and will be in the form of a written summary. If you wish to receive this, please indicate on the relevant section of the consent form. Any papers that may be published arising from the research can be accessed on request.

What do I do if I have concerns about this research?
If you have any concerns regarding the nature of this project then you should contact the Lead Researcher, Richard Ellis, 921-9999 ext 7612.
If you have any questions or concerns about your rights as a participant in this research study you can contact an independent health and disability advocate. This is a free service provided under the Health and Disability Commissioner Act.
Telephone: (NZ wide): 0800 555 050
Free Fax (NZ wide): 0800 2787 7678 (0800 2 SUPPORT)
Email (NZ wide): advocacy@hdc.org.nz

Who do I contact for further information about this research?
Researcher contact details:
Richard Ellis, work phone: 921-9999 ext 7612, richard.ellis@aut.ac.nz

Project Supervisor contact details:
Dr Wayne Hing, work phone: 921-9999 ext 7800

This study has received ethical approval from the Health and Disability Ethics Committee (Northern Y Regional Ethics

Committee) on 22 January, 2008. Ethics reference no.: NTY/07/12/131

APPENDIX 5

Consent to Participation in Research
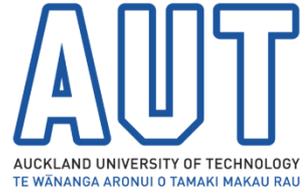
Title of Project:
Can measurement of peripheral nerve movement
strengthen and support the clinical findings of
neurodynamic tests?

Project Supervisor: Dr. Wayne Hing
Researcher: Richard Ellis

I have read and understood the information provided about this research project
(Information Sheet dated 21st November, 2007.).

I verify that I do not meet any of the Exclusion Criteria detailed in the Information
Sheet (namely if you have a history of major trauma or surgery of the lumbar spine,
pelvis or upper leg, please do not volunteer).

I have had an opportunity to ask questions and to have them answered.

I understand that I may withdraw myself or any information that I have provided for this
project at any time prior to completion of data collection, without being disadvantaged
in any way.

I agree to take part in this research.

I consent to have the results of this study disseminated with my General Practitioner
(GP)
I wish to receive a copy of the report from the research: tick one: Yes   O   No   O

Participant signature: ....…………………...

Participant name: …………………………………………………………….

Participant Contact Details (if appropriate):

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……………………………………………………………………………………..
Date:
…………………………………………………

APPENDIX 6

Participant Information Sheet

Date Information Sheet Produced:
07 April, 2010

Project Title
**Neurodynamic evaluation of the sciatic nerve using ultrasound imaging:
Examination of the clinical implications of sciatic nerve movement during
neurodynamic sliders and tensioners**

Invitation
You are invited to take part in a research study performed as part of the requirements for
completion of a PhD thesis, conducted by Richard Ellis and Dr. Wayne Hing (Primary
Supervisor). Information from this research will be presented within a written thesis (as per the
requirements of a PhD) and may also be presented within academic publications or verbal
presentations.
Participation is completely voluntary and you may withdraw from the study at anytime without
giving a reason or being disadvantaged.

What is the purpose of this research?
To determine and compare the longitudinal excursion of the sciatic nerve during different neural
mobilisation exercises (exercises that encourage nerve movement).

How are people chosen to be asked to be part of this research?
People with 'normal' sciatic nerve function will be asked to volunteer to take part in the study.
If you have a history of lumbar spine or pelvic problems or upper leg or spinal surgery, please
do not volunteer.

What happens in this research?
You will be asked to be seated in a Biodex dynamometer (a laboratory sitting platform) with
your leg comfortably supported. An image of your sciatic nerve (through the hamstring
muscles) using Diagnostic Ultrasound is taken. Images will be taken during a sequence of
gentle leg and neck movements. The probe of the machine will be applied to the skin surface
with water-based, transmission gel and moved around until a clear image is achieved. The
image will show on a monitor from which recordings and calculations can be made. You will
be required to wear shorts so that the ultrasound probe can be applied to the back of your thigh.

What are the discomforts and risks?
There are no risks or discomfort from the ultrasound scanning. The transmission gel is water-
based thus precluding an allergic reaction. The researcher and Biodex 3 dynamometer will
assist you with the gentle leg movements and these will be performed without discomfort.

What are the benefits?
The benefit of performing this research is to provide evidence to support the use of neural
mobilisation exercises in the clinical setting and to establish which exercises allows for the
greatest amount of nerve movement therefore providing the best therapeutic treatment for nerve
pathologies.

What compensation is available for injury or negligence?
In the unlikely event of a physical injury as a result of your participation in this study, rehabilitation and compensation for injury by accident may be available from the Accident Compensation Corporation, providing the incident details satisfy the requirements of the law and the Corporation's regulations.

How will my privacy be protected?
Your privacy will be protected by identifying you only by a number. Access to the data is restricted to the researchers.

What are the costs of participating in this research?
There is no monetary cost. It will however cost approximately 60 minutes of your time in total.

What opportunity do I have to consider this invitation?
Before volunteering, please consider carefully whether you are prepared to be part of the study. There will be some flexibility around the appointment times for the data collection. Please communicate clearly with us so convenience is optimised for all concerned, and appointments run smoothly and are on time.

How do I agree to participate in this research?
You will need to read and sign a Consent Form in order to participate in this study. A consent form can be obtained from the researcher (see contact details below).
Please contact the researcher if you wish to join this study. You will be contacted prior to the start of data collection which is scheduled for between July and December, 2010. This may be slightly earlier or later depending on how the set up of the study progresses.

Will I receive feedback on the results of this research?
Results will be made available to you at the completion of the study, and will be in the form of a written summary. If you wish to receive this, please indicate on the relevant section of the consent form. Any papers that may be published arising from the research can be accessed on request.

What do I do if I have concerns about this research?
If you have any concerns regarding the nature of this project then you should contact the Project Supervisor, Dr Wayne Hing, 921-9999 ext 7800.
Any concerns regarding the conduct of the research should be made to the Executive Secretary, AUTEC, Madeline Banda, madeline.banda@aut.ac.nz , 921 9999 ext 8044.

Who do I contact for further information about this research?

Who do I contact for further information about this research?
Researcher contact details:
Richard Ellis, work phone: 921-9999 ext 7612, richard.ellis@aut.ac.nz

Project Supervisor contact details:
Dr Wayne Hing, work phone: 921-9999 ext 7800

APPENDIX 7

Consent to Participation in Research

Title of Project: Neurodynamic evaluation of the sciatic nerve using ultrasound imaging: Examination of the clinical implications of sciatic nerve movement during neurodynamic sliders and tensioners

Project Supervisor: Dr. Wayne Hing
Researcher: Richard Ellis

I have read and understood the information provided about this research project (Information Sheet dated 7th April, 2010).

I verify that I do not meet any of the Exclusion Criteria detailed in the Information Sheet (namely if you have a history of lumbar spine or pelvic problems or upper leg or spinal surgery, please do not volunteer).

I have had an opportunity to ask questions and to have them answered.

I understand that I may withdraw myself or any information that I have provided for this project at any time prior to completion of data collection, without being disadvantaged in any way.

I agree to take part in this research.

I wish to receive a copy of the report from the research: tick one: Yes   O   No   O

Participant signature: ....………………………..

Participant name: …………………………………………………………….

Participant Contact Details (if appropriate):

…………………………………………………………………………………………..
…………………………………………………………………………………………..
Date:

Approved by the Auckland University of Technology Ethics Committee on 28 May 2010 AUTEC Reference number 10/70

Note: The Participant should retain a copy of this form.

APPENDIX 8

![AUT University logo - Te Wānanga Aronui o Tamaki Makau Rau]

M E M O R A N D U M

Auckland University of Technology Ethics Committee (AUTEC)

To: Wayne Hing
From: **Madeline Banda** Executive Secretary, AUTEC
Date: 28 May 2010
Subject: Ethics Application Number 10/70 **Neurodynamic evaluation of the sciatic nerve using ultrasound imaging: Examination of the clinical implications of sciatic nerve movement during neurodynamic sliders and tensioners.**

Dear Wayne

Thank you for providing written evidence as requested. I am pleased to advise that it satisfies the points raised by the Auckland University of Technology Ethics Committee (AUTEC) at their meeting on 10 May 2010 and that I have approved your ethics application. This delegated approval is made in accordance with section 5.3.2.3 of AUTEC's *Applying for Ethics Approval: Guidelines and Procedures* and is subject to endorsement at AUTEC's meeting on 14 June 2010.

Your ethics application is approved for a period of three years until 28 May 2013.

I advise that as part of the ethics approval process, you are required to submit the following to AUTEC:

- A brief annual progress report using form EA2, which is available online through *http://www.aut.ac.nz/research/research-ethics*.   When necessary this form may also be used to request an extension of the approval at least one month prior to its expiry on 28 May 2013;

- A brief report on the status of the project using form EA3, which is available online through *http://www.aut.ac.nz/research/research-ethics*. This report is to be submitted either when the approval expires on 28 May 2013 or on completion of the project, whichever comes sooner;

It is a condition of approval that AUTEC is notified of any adverse events or if the research does not commence. AUTEC approval needs to be sought for any alteration to the research, including any alteration of or addition to any documents that are provided

to participants. You are reminded that, as applicant, you are responsible for ensuring that research undertaken under this approval occurs within the parameters outlined in the approved application.

Please note that AUTEC grants ethical approval only. If you require management approval from an institution or organisation for your research, then you will need to make the arrangements necessary to obtain this. Also, if your research is undertaken within a jurisdiction outside New Zealand, you will need to make the arrangements necessary to meet the legal and ethical requirements that apply within that jurisdiction.

When communicating with us about this application, we ask that you use the application number and study title to enable us to provide you with prompt service. Should you have any further enquiries regarding this matter, you are welcome to contact Charles Grinter, Ethics Coordinator, by email at ethics@aut.ac.nz or by telephone on 921 9999 at extension 8860.

On behalf of the AUTEC and myself, I wish you success with your research and look forward to reading about it in your reports.

Yours sincerely

Madeline Banda
Executive Secretary
Auckland University of Technology Ethics Committee

Cc: Richard Ellis richard.ellis@aut.ac.nz