THE SLUMP TEST AND POSTERIOR THIGH DISORDERS

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Abbreviations

AFL: Australian Football League
ANOVA: Analysis of Variance
BASRaT: British Association of Sports Rehabilitators and Trainers
BPTT: Brachial Plexus Tension Test
CCLF: contralateral cervical lateral flexion
CCSF: Contralateral cervical side flexion
C7: 7th vertebra of the cervical spine
CT: Computed Tomography
EIS: English Institute of Sport
GP: General Practitioner
L1: first lumbar vertebra
L2: second lumbar vertebra
L3: third lumbar vertebra
L4: fourth lumbar vertebra
L5: fifth lumbar vertebra
L5/S1: The intervertebral level of the spine corresponding to the disc between L5 and S1 vertebrae.
ICC: Intra-class correlation coefficient
M1: Onset of muscle activity
M1BF: Onset of muscle activity of Biceps Femoris muscle
M1ST: Onset of muscle activity of Semitendinosus muscle
MRI: Magnetic Resonance Scanning
NMJ: Neuromuscular junction
P1: Onset of pain
PA: Posterior anterior
PAIVM: Posterior anterior intervertebral motion
PTI: Posterior Thigh Injury
R1: Onset of resistance
ROI: Region of interest
ROM: Range of motion
SANFL: South Australian National Football League
SD: Standard Deviation
SDD: Smallest detectable difference
SEM: Standard error of mean
SQRT: Square root
S1: first sacral vertebra of the spine
S2: second sacral vertebra of the spine
TIFF: Tagged Image File Format
UCAS: University and Colleges Admissions Services
ULNT: Upper Limb Neurodynamic Test
ULTT1: Upper limb tension test 1
UK: United Kingdom
VAS: Visual Analogue Scale
VTI: Velocity time integrals
Abstract

Introduction: The slump test is used in athletes with suspected hamstring strains to determine the presence of neural mechanosensitivity. Other than cadaveric investigations, limited evidence exists regarding this test with respect to the neuromuscular system.

Aim: To examine the effect of the slump test on local muscular and neural structures in the posterior thigh in athletes with hamstring injury.

Methods: Electromyography and ultrasound were utilised to determine hamstring muscle activity onset and sciatic nerve excursion respectively. Predictability of the slump test with respect to hamstring injury occurrence was also investigated.

Results: 96% (n=26) of therapists used the slump test diagnostically, whilst 63% utilised it as a treatment tool. The slump test was ineffective at predicting hamstring injury occurrence. In hamstring injured athletes (n=10) the slump test with cervical flexion, was found to activate biceps femoris significantly earlier (p<0.008) than semitendinosus, also pain and resistance, in the injured limb. Reduced sciatic nerve longitudinal excursion in the injured limb of two athletes with no radiological evidence of hamstring muscle damage was observed during the slump test with cervical flexion and ankle dorsi-flexion; a finding not replicated in the one athlete who had an actual hamstring muscle injury.

Conclusions: Biceps femoris appears to act to protect the local neural system in the posterior thigh in hamstring injured athletes. Considering two athletes with posterior thigh pain had no muscle damage to the hamstring muscles, yet presented with reduced sciatic nerve excursion in the injured limb during the
slump test, the possibility of biceps femoris acting to protect the nervous system is feasible. This thesis is novel in its demonstration of the protective nature of biceps femoris acting during the slump test, in addition to quantifying sciatic nerve excursion in athletes with posterior thigh pain.
Chapter 1

Introduction and Review of the Literature

1.1 Introduction

In a clinical setting, therapists traditionally assess the sensitivity of peripheral nerves to movement using neurodynamic tests (Boyd et al., 2009). The slump test is one such test which is advocated for use in patients with spinal and lower limb pain (Philip et al., 1989) and apparent hamstring strains (Turl and George, 1998). The slump test involves placing the patient in a seated position, with the popliteal crease of both legs against the edge of a table or plinth. The patient is then requested to slump their shoulders (i.e. thoracic flexion), whilst maintaining the sacrum in a vertical position, following which, the examiner applies overpressure to the cervical spine. The ankle is then passively dorsi-flexed and the knee moved from approximately 90° flexion into extension (Figure 1.1).
The range of knee extension achieved during the slump test in a clinical setting is dependent on whether the clinician wants to detect an onset of resistance to movement (Herrington et al., 2008) or whether the examiner wants the patient to report onset of pain or sub-maximal pain (Coppieters et al., 2002). Onset of muscle activity with respect to the joint angle achieved by the moving
joint is another response regarded by Hall et al. (1998) as an appropriate measurement to obtain during neurodynamic testing. All of the aforementioned variables are responses frequently obtained during neurodynamic testing, yet are ones which to date, have not been viewed simultaneously during the slump test. This is therefore the focus of one of the primary studies within this thesis, conducted in a sample population of athletes with a clinically diagnosed hamstring strain.

Structural differentiation, via cervical extension or ankle plantar-flexion, is undertaken during the slump test, to determine whether the nervous system is contributing to the patient's symptoms. A positive slump test is constituted by a reproduction or increase in symptoms during cervical flexion which are then alleviated during cervical extension (Maitland, 1985), difference in responses between limbs (Butler, 2000), available range of motion at the knee joint (Butler and Gifford, 1989, Coppieters et al., 2002) or structural differentiation supporting a neurogenic source (Butler, 2000).

Whilst early research into neurodynamics examined the effects of trunk and lower limb motion on the spinal cord and peripheral nerves in cadaver specimens (Inman and Saunders, 1942, Falconer et al., 1947, Smith, 1956; Breig and Marions, 1963, Goddard and Reid, 1965) the slump test has been relatively ignored in research conducted in-vivo, with upper limb neurodynamic tests dominating this field of research (Coppieters et al., 2009, Dilley et al., 2003, Dilley
et al., 2007, Hough et al., 2007). This author can only assume the preference in examining upper limb neurodynamic tests in-vivo is due to the ease at which these tests can be conducted. The slump test is a gross, multi-joint test, which requires considerable dexterity by a clinician or researcher and can therefore prove to be a difficult test to conduct. Despite this however, Ellis et al. (2008) investigated the reliability of measuring the excursion of the sciatic nerve during a modified slump test using high frequency ultrasound. Consequently, one study in this thesis has intrinsically examined the excursion of the sciatic nerve in-vivo during a modified slump test in athletes with a posterior thigh injury, also using high frequency ultrasound.

The slump test is advocated for use in the diagnostic process of posterior thigh pain in athletes (Turl and George, 1998), with an aim to determining whether the symptoms experienced by the patient are primarily caused by muscular or neural structures. A positive slump test, and therefore neural mechanosensitivity, has been associated with athletes suffering from recurrence of hamstring injury (Turl and George, 1998). Turl and George (1998) and Shacklock (2005a) both suggest that adhesion of the sciatic nerve can occur as a consequence of hamstring injury; hence the mechanosensitivity reported during the slump test by the former authors. Carmody and Prietto (1995) reported a case study of significant entrapment of the sciatic nerve in the posterior thigh following a traumatic injury to biceps femoris. Considering the intimate location of the sciatic nerve to the hamstring muscles, in particular biceps femoris, a muscle
which it travels through (Figure 1.2), the possibility of neural entrapment is realistic, yet to date is an unverified theory in hamstring injured athletes. In Figure 1.2, the sciatic nerve is clearly visible in close proximity to the short head of biceps femoris; the long head of biceps femoris is absent from the diagram and typically lies superficial to the sciatic nerve crossing the posterior thigh from the ischial tuberosity and sacrotuberous ligament to the lateral aspect of the knee (Carlson, 2008).

Figure 1.2: The sciatic nerve in the posterior thigh.
Considering the high injury and re-injury rates of hamstring injury in athletes (Hawkins and Fuller, 1999, Hawkins et al., 2001, Walden et al., 2005), it is surprising that larger volumes of research has not sought to examine the potential neural involvement which may co-exist with hamstring injury. Consequently, the studies conducted in this thesis all aim to collaborate to provide even further insight into the slump test in hamstring injured athletes, with the aim of expanding on the current research available in neurodynamics.

1.2 Review of Literature

The subsequent sections of this chapter presents literature which encompasses the theme of this thesis; the slump test and hamstring injury. The concept of neurodynamics is initially discussed, followed by the nucleus of this research project; the slump test. Subsequent to this, the effect neurodynamic testing has on peripheral nerves is presented, in addition to the validity and reliability of these clinical tests. The focus of the literature review then addresses the other important factor of this thesis; hamstring injury. The overall aim and objectives of this thesis conclude this chapter.
1.2.1 The Slump Test

Neurodynamic tests were developed to evaluate peripheral nerve sensitivity to movement and to infer underlying pathomechanics (Boyd et al., 2005). The aim of incorporating these tests into a clinical examination is to move the neural tissues to gain an impression of their sensitivity to mechanical strain (Shacklock, 1995). The primary intention of these tests is to determine if the neural system has a role to play in the symptoms experienced by a patient; a task achieved during neurodynamic testing by moving the neural structure in the area in question, without moving the musculoskeletal tissues in the same region (Shacklock, 2005b). This is a manoeuvre known as structural differentiation and enables a therapist to differentiate between neurogenic symptoms and those of musculoskeletal origin (Shacklock, 2005b). Therefore, neurodynamic tests are important in the assessment of suspected neuropathic conditions.

A common, yet under-researched neurodynamic test used in the diagnostic process for patients with spinal and lower limb pain (Philip et al., 1989) and apparent hamstring strains (Turl and George, 1998) is the slump test (Maitland, 1979). The slump test is utilised to evaluate the sensitivity of the central and peripheral nervous systems to movement, from the head, along the spinal cord and sciatic nerve tract (Shacklock, 2005a). The slump test is an example of using the points of nervous system fixation at each end of the nerve tract to apply elongation forces to the system. The nervous system is proximally
attached to the cranium via dura and distally via termination of the digital nerves in the toes. Therefore, movements which increase the distance between these end points, such as which occurs in the slump test, will assess a nerve’s sensitivity to elongation (Shacklock, 2005a). Whilst in-vivo research into the slump test may be lacking, the biomechanical rationale behind this test may be extrapolated from early cadaveric work (Inman and Saunders, 1942, Falconer, 1947, Goddard and Reid, 1967, Smith, 1956).

Inman and Saunders (1942) demonstrated the effect trunk and limb movement has the spinal nerves during the straight leg raise (SLR), a manoeuvre which involves progressively increasing hip flexion as the knee joint remains extended, to cause distal excursion of the nerve root in the spinal foramen in the fourth and fifth lumbar levels (L4 and L5 respectively); with no motion evident at the upper lumbar nerves (L1 and L2). Between 60° and 80° hip flexion during the SLR, the most notable movement occurred at L5, S1 and S2 nerve segments, ranging from 2mm to 5mm. Alternatively however, flexion of the spine caused proximal migration of the upper lumbar nerves with little or no movement evident in the lower lumbar nerves at L4 and L5 in Inman and Saudner’s (1942) study.

Falconer et al. (1947) supports the aforementioned authors having demonstrated the effects of the SLR on the cauda equina in cadavers, whereby the nerves at the L5 and S1 levels moved in a distal direction of 2mm to 6mm as the hip moved into flexion. The greater the degree of flexion imposed on the hip,
the greater the magnitude of movement by L5 and S1 nerves. The authors observed the fourth lumbar nerve to undergo minimal movement as a consequence of the SLR, with no excursion evident in the remaining lumbar nerves (L1, L2 and L3).

Goddard and Reid (1965) concurred with Inman and Saunders (1942) and Falconer et al. (1947), reporting the SLR to cause the greatest amount of movement of the first sacral nerve with movement of the fifth lumbar nerve being on average 3mm. No movement was evident in the third lumbar nerve. The authors also discovered the largest amount of movement of the sciatic nerve occurred in its most distal regions during the SLR with progressively more movement occurring in the more proximal segments as the hip was progressively moved into greater degrees of flexion.

All three studies agree that flexion of the hip as the knee maintains in an extended position (i.e. SLR), causes distal excursion of the lower lumbar spinal nerves; with little movement evident in the higher level nerves. Alternatively however, Inman and Saunders (1942) discovered the lower lumbar nerves (L4 and L5) to remain unaffected by spinal flexion; a manoeuvre which caused movement of the more proximal lumbar nerves (L1 and L2).

In a modified straight leg raise (SLR) whereby monkeys were placed on their side, Smith (1956) discovered that hip flexion, knee extension and ankle
dorsi-flexion placed traction on the lumbosacral trunk thereby stretching the spinal canal. At the lumbosacral trunk, the authors actually reported nerve movement of $4.0\text{mm}$ in one monkey, with movement evident as high as the C8 nerve root. Smith’s (1956) work also demonstrated the convergence of peripheral nerves; a topic which shall be discussed later in this chapter (section 1.2.2). The authors discovered that isolated knee extension causes distal and proximal excursion of the sciatic and posterior tibial nerves respectively. When sole hip flexion was executed, the sciatic nerve moved towards the hip, whilst with ankle dorsi-flexion alone, the posterior tibial nerve moved towards the ankle joint.

During flexion of the trunk and neck, from a fully extended position, all segments of the spinal cord and the hindbrain were discovered by Smith (1956) to move towards the disc between the fourth and fifth cervical vertebrae during flexion of the trunk and neck. However from the mid-cervical to mid-thoracic regions for the same movements, each successive segment of the cord moved towards the head, progressively more. Between T1 and T6, the spinal cord moved between $1.7\text{mm}$ and $5.9\text{mm}$; the greater movement being evident at the latter level. Below T6, movement of the cord nonetheless occurred in a proximal direction; but a progressive reduction in the magnitude of movement was evident at lower levels of the spine. Despite this however, the cord moved $4.0\text{mm}$ at L4 as a consequence of head and trunk flexion.
As early as 1942, Inman and Saunders (1942) postulated that a clinical test incorporating spinal flexion and the straight leg raise would aid in the localisation of clinical signs, allowing therapists to detect lesions involving the upper or lower spinal nerves. The slump test is a rare neurodynamic test incorporating both the entire trunk and the lower limb. Taking into account the early cadaveric findings (Inman and Saunders, 1942, Falconer, 1947, Goddard and Reid, 1967, Smith, 1956), it is feasible that maintaining the head, trunk and hip in flexion and ankle in dorsi-flexion, whilst applying knee extension will generate tension along the spinal cord and lower limb peripheral nerves. These early in-vitro studies support the use of the slump test as a diagnostic tool when assessing the sensitivity of a nerve to movement.

The slump test is advocated to be utilised during the clinical examination of patients who present with spinal symptoms (Butler, 1991), spinal, pelvic and lower limb conditions or whereby pain is experienced in the neural distribution of the sciatic nerve and its extensions (Shacklock, 2005a). A positive neurodynamic test is interpreted as changes in neural dynamics (Greening, 2006) and indicative of mechanosensitivity or reduced nerve movement (Butler, 1991). Whilst it cannot eliminate the presence of muscle damage in a hamstring injured athlete, it can assist the therapist in determining whether the sciatic nerve or its branches are sensitive to movement, thereby subsequently requiring treatment.
The slump test utilises the continuum of the nervous system in a logical progression (Butler, 1991). In the completed slump position (with cervical flexion), the limitation of any further knee extension may be due to the peripheral and central nervous systems being fully elongated. Whilst other anatomical structures, such as fascia, may be a plausible explanation for the inability to gain further movement in the moving joint (i.e. the knee) during the slump test, the nervous system has the most direct structural connection (Butler, 1991).

Consequently, it is possible that the nervous system may undergo greatest strain during the slump test than the surrounding anatomical structures, and therefore be the primary cause of symptom production during this test. However, what actually occurs to the neural tissues during the slump test is currently unknown and can only be extrapolated from the in-vivo and in-vitro work conducted by various authors, primarily in the upper limb (Coppieters et al., 2006a, Dilley et al., 2003, Dilley et al., 2007, Hough et al., 2007). The next section of this chapter focuses on the research which has investigated the effect joint movement and neurodynamic testing has on peripheral nerve movement; the findings of which aid the development of treatment strategies, such as tensioning and sliding techniques, for clinicians to use in patients with suspected neural pathology.
1.2.2 Neurodynamic Tests and Nerve Excursion

Peripheral nerves must slide, elongate and return to resting length, to accommodate changes in nerve bed length during joint movements (Dilley et al., 2007). The nerve bed, also known as the mechanical interface, comprises of any structure which resides next to the nervous system (e.g. tendon, muscle, fascia, blood vessel etc.) (Shacklock, 2005a). Movements which produce natural elongation of the nerve bed cause increased strain within the corresponding nerve and excursion of that nerve segment towards the moving joint; a concept referred to as convergence (Coppieters et al., 2006a). When a nerve realigns along a shortening nerve bed by gliding away from a joint and thereby undergoes reduced strain, this is termed "divergence" (Wright et al., 2001).

Excursion of a nerve, which can be transverse or longitudinal (Shacklock, 1995) relates to the gliding of a nerve, relative to the surrounding nerve bed and is measured in millimetres (mm) (Dilley et al., 2003, Erel et al., 2003, McLellan and Swash, 1976). Longitudinal nerve movement is vital as it enables a nerve to adapt to changes in nerve bed length (Dilley et al., 2003) and alterations in such can have pathological consequences (Hough et al., 2007). The distribution of an applied force to the nervous system is not uniform or equally dispersed over the whole nervous system (Butler, 1991), as shall be highlighted in the research subsequently discussed. The movement of a nerve is possible by the gliding occurring between the vascularized and avascularized layer of connective tissue.
surrounding the nerve (Lang, 1962). Ideal conditions allow gliding with minimal friction between the surrounding structures. If layers of the gliding apparatus become fibrotic, efficient nerve gliding is not possible and the nerve can become adherent to surrounding structures (Millesi et al., 1990). Under conditions such as this, the distribution of forces along a nerve segment is not possible (Millesi et al., 1990).

Determining the normal movement pattern of nerves in healthy asymptomatic individuals is important to undertake as it enables comparisons to be made for conditions where altered nerve sliding may be implicated, such as Carpal Tunnel Syndrome (Hough et al., 2007). Several investigations have been undertaken in-vitro and in-vivo to determine the effect joint movement, as part of neurodynamic testing, has on the biomechanical properties of peripheral nerves in the upper and lower limb (Babbage et al., 2007, Boyd et al., 2005, Coppieters et al., 2006a, Dilley et al., 2003, Dilley et al., 2007). Boyd et al. (2005) evaluated the excursion of the sciatic nerve in euthanised (EUTH) and anaesthetised (LIVE) rats during a modified SLR. The authors reported significant (p< 0.0001) proximal excursion of the sciatic nerve when 110° of hip flexion was added to 75° knee flexion and 50° ankle plantar flexion during a modified SLR (EUTH 2.43mm; LIVE 2.75mm). When the ankle position was then altered to 10° dorsi-flexion, significant excursion of the sciatic nerve also occurred, but this time in a distal direction (EUTH 0.54mm; LIVE 1.64mm; p=0.0026).
In a study conducted on canines, Babbage et al. (2007) reported isolated stifle joint extension to cause significant distal excursion of the sciatic nerve (10±1.0mm; p=0.0002), whilst hip flexion, conducted as a sole movement, induced significant distal excursion of the sciatic nerve, but of a lesser magnitude (1.8±0.8mm; p=0.02). Boyd et al. (2005) and Babbage et al. (2007) both demonstrated how the nerve segment nearest the moving joint during a neurodynamic test, moves in the direction of the joint when the nerve bed length of that nerve is increased. The aforementioned studies, despite being conducted on animals thereby restricting the direct application of findings to humans, both highlight one of the innate biomechanical properties of nerves; that movement of a joint which elongates the nerve bed length of that nerve will cause excursion of a nerve towards the moving joint.

Coppieters et al. (2006a) concurred with the findings of the animal studies, having investigated the strain and longitudinal excursion of the sciatic and tibial nerves in the lower limb during a modified Straight Leg Raise (SLR) in eight embalmed human cadavers. The authors first sought to determine the effect isolated ankle dorsi-flexion had on the sciatic and tibial nerves followed then by hip flexion with ankle dorsi-flexion and knee extension (i.e. SLR). The overall finding by Coppieters et al. (2006a) was that the largest longitudinal excursion of the tibial and sciatic nerves during the SLR and isolated dorsi-flexion occurred in the nerve segment nearest the moving joint, with the respective nerve moving towards the joint (Table 1.1).
Table 1.1: Longitudinal excursion of the sciatic nerve in embalmed human cadavers during a modified Straight Leg Raise.

<table>
<thead>
<tr>
<th>SD manoeuvre</th>
<th>Nerve examined</th>
<th>Distance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isolated ankle dorsi-flexion</td>
<td>Tibial nerve at ankle</td>
<td>+9.5mm*</td>
</tr>
<tr>
<td></td>
<td>Tibial nerve at knee</td>
<td>+3.1mm*</td>
</tr>
<tr>
<td></td>
<td>Sciatic nerve distal to greater trochanter</td>
<td>+Non significant.</td>
</tr>
<tr>
<td>Hip flexion with ankle dorsi-flexion and knee extension maintained</td>
<td>Sciatic nerve distal to greater trochanter</td>
<td>-28.0mm*</td>
</tr>
<tr>
<td></td>
<td>Tibial nerve at knee</td>
<td>-12.2mm*</td>
</tr>
<tr>
<td></td>
<td>Tibial nerve at ankle</td>
<td>-6.4mm*</td>
</tr>
</tbody>
</table>

*Significant excursion of the nerve (p<0.05).

"+" Denotes distal excursion of the nerve.

"-" Denotes proximal excursion of the nerve.

"SD" manoeuvre: Structural differentiation manoeuvre.

Adapted from Coppieters et al. (2006a).

When the tibial nerve was examined by Coppieters et al. (2006a) at the ankle during isolated dorsi-flexion, it moved the greatest distance of all the nerves examined (9.5mm) (Table 1.1). However, during the same movement, the tibial nerve, when examined at the knee, moved only 3.1mm. At both locations for the tibial nerve during dorsi-flexion alone, the nerve moved in the direction of the ankle; the joint where the movement occurred. During the SLR (i.e. hip flexion with ankle dorsi-flexion and knee extension maintained), the sciatic nerve at the proximal posterior thigh moved the greatest distance of the other nerves examined (28.0mm), towards the hip joint (Table 1.1). Whilst the tibial nerve at
the knee and ankle joints also moved towards the hip joint during the SLR, the extent of excursion was less than that of the sciatic nerve (12.2mm and 6.4mm respectively).

The magnitude of excursion of the nerves during neurodynamic tests is potentially related to the degree of strain imparted on nerve segments during these tests. In Coppieters et al's (2006a) study, isolated ankle dorsi-flexion caused not only significantly greater excursion of the tibial nerve at the ankle, but also significantly greater strain. However, despite the tibial nerve at the knee undergoing significant excursion for this manoeuvre, no significant increase in strain was discovered for this nerve segment or for the sciatic nerve in the posterior thigh. Alternatively however, when hip flexion was conducted during the SLR with ankle dorsi-flexion, significantly greater strain was evident in the sciatic and tibial nerves; a finding not seen in some of the distal nerve segments examined, such as the lateral plantar nerve.

It appears that moving joints, which are an integral component of neurodynamic tests, cause increased strain, not only within the nerve segments in close proximity but also along the tract of the nerve being examined. Ankle dorsi-flexion in isolation in Coppieters et al's (2006a) study caused only local nerve segments to display increased strain and excursion. However, when the actual SLR was conducted, increased strain was evident along the sciatic, tibial and medial plantar nerves, with the greatest strain and excursion evident at the
more proximal locations. Peripheral nerves therefore appear to cope with multiple joint movements by moving towards the moving joint and dissipating strain along the course of its tract to nerve segments quite remote from the site of the moving joint. These biomechanical functions potentially occur to minimise risk of injury to the peripheral nerves.

The in-vitro studies (Babbage et al., 2007, Boyd et al., 2005, Coppieters et al., 2006a) demonstrated how the greatest longitudinal excursion of a nerve occurs at the moving joint and in the direction of the moving joint; the latter concept being defined as “convergence” (Shacklock, 2005a). The findings from the animal and human cadaver studies should be interpreted with caution however, as the results cannot be extrapolated directly to in-vivo humans or animals. Also to note is that during the process for evaluating nerve excursion in cadavers, disruption of the surrounding tissues can occur; the extent to which is not generally reported in these studies. Dissection of muscle, fascia and tendon through which a nerve traverses can potentially allow greater nerve excursion as there may be less of a mechanical interface for the nerve to pass through.

Coppieters et al. (2006a) acknowledge the effect dissection can have on the tissues during the SLR as the authors transected the Achilles tendon to obtain a physiological range of ankle dorsi-flexion, thereby, by their own admission, potentially altering strain in the plantar fascia during the hip flexion component of the SLR. Therefore, greater ranges of nerve excursion with
concomitant deceases in strain may be present in cadaver specimens who undergo excessive dissection than in those whereby minimal disruption of surrounding tissues has taken place.

Another primary concern when neurodynamic tests are conducted on cadavers is the naturally diminished range of motion available at the joints. Neurodynamic tests, particularly those of the lower quadrant, are gross tests which incorporate numerous joints, for example, the hip, knee and ankle are incorporated in the straight leg raise. Producing fluid movement, through range, at these joints may be difficult during complex neurodynamic tests due to the innate stiffness of the participating joints and therefore compromise the transferability of findings from these in-vitro studies to in-vivo populations (Kleinrensink et al., 1995). However, research in the past decade has evolved to permit the in-vivo examination of peripheral nerves during neurodynamic tests. Using high-frequency ultrasonography, the effect joint movement has on nerve excursion in healthy and symptomatic populations has been investigated (Dilley et al., 2003, Dilley et al., 2007; Hough et al., 2007).

Dilley et al. (2003) investigated the effect several upper limb joint movements which are typically used in an upper limb neurodynamic test for the median nerve, had on the strain and longitudinal excursion of the nerve, using high-frequency ultrasonography. Strain was defined by the authors as the percentage elongation of the nerve and was estimated from the difference in
nerve excursion at two ultrasound transducer locations, divided by the distance between those locations. The authors' findings (Table 1.2) concur with the in-vitro studies; the nerve segment nearest the moving joint moves in the direction of the joint, and to a greater extent than nerve segments at more remote locations.

This is evident for the median nerve when imaged in the forearm and upper arm, when the wrist is moved from neutral into 40° extension whilst the shoulder is maintained in 45° abduction and the elbow in full extension. The greatest movement of the median nerve occurred in the forearm (4.7mm) than upper arm (2.4mm), with both segments of the nerve moving towards the wrist joint. Similarly, a greater increase in percentage strain of the median nerve was evident in the distal forearm (1.5%) than the proximal forearm (1.1%) with wrist extension, inferring that peripheral nerves cope with increasing strain by elongating and dissipating the strain along the course of the nerve tract, with the segment in closest proximity being subjected to the highest levels of strain and excursion.
Table 1.2: Longitudinal excursion of the median nerve during various limb movements.

<table>
<thead>
<tr>
<th>Joint positions maintained</th>
<th>Moving joint</th>
<th>Excursion of median nerve</th>
<th>Forearm Strain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shoulder at 45° abduction</td>
<td>Wrist</td>
<td>+ 4.7mm</td>
<td>1.1% (P)</td>
</tr>
<tr>
<td>Elbow at 0°</td>
<td>From neutral to 40° extension</td>
<td>+ 2.4mm</td>
<td>1.5% (D)</td>
</tr>
<tr>
<td>Shoulder at 90° abduction</td>
<td>Wrist</td>
<td>+ 4.2mm</td>
<td>1.1% (P)</td>
</tr>
<tr>
<td>Elbow at 0°</td>
<td>From neutral to 40° extension</td>
<td>+ 1.8mm</td>
<td>2.0% (D)</td>
</tr>
<tr>
<td>Wrist at 0°</td>
<td>Shoulder joint</td>
<td>- 3.4mm</td>
<td>- 5.2mm</td>
</tr>
<tr>
<td>From 10° to 90° abduction</td>
<td>Elbow</td>
<td>- 3.0mm</td>
<td>0.6%</td>
</tr>
<tr>
<td>From 90° to neutral</td>
<td>Neck</td>
<td>- 0.3mm</td>
<td>0.1% (P)</td>
</tr>
<tr>
<td>From neutral to 35°</td>
<td>Neck</td>
<td>- 0.8mm</td>
<td>0.2% (P)</td>
</tr>
<tr>
<td>contralateral side flexion</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

"0°"=joint is straight

"+" Denotes distal excursion of the nerve

"-"Denotes proximal excursion of the nerve

"P"=proximal forearm strain

"D"=distal forearm strain.

Adapted from: Dilley et al. (2003).
When the same wrist movement (neutral to 40° extension) was carried out, but with 45° more shoulder abduction, the magnitude of nerve movement was less for both segments of the median nerve (forearm 4.2mm; upper arm 1.8mm). However, the percentage strain of the median nerve in the distal forearm increased by 0.5% as a result of 45° greater shoulder abduction; results which suggest that strain and excursion within the median nerve is dependent on the magnitude of shoulder abduction.

Maintaining the shoulder and wrist in a static position and moving the elbow from 90° flexion to neutral, caused the median nerve in the forearm to move proximally by 3.0mm, whilst the same nerve, but at a different location in the upper arm, moved 10.4mm, but in a distal direction (Table 1.2). When the participants of Dilley et al’s (2003) study executed contralateral side flexion of the neck, whilst maintaining the shoulder, elbow and wrist in static positions, the median nerve moved in a proximal direction towards the cervical spine, at both locations where the nerve was imaged (forearm 0.3mm; upper arm 0.5mm). Relatively small increases in percentage strain were evident in the median nerve in the forearm for all the aforementioned manoeuvres, ranging from 0.1% to 0.6% (Table 1.2).

What is evident from Dilley et al’s (2003) study is that moving joints remote to nerve segments can nonetheless cause increases in strain within the nerve, with concomitant nerve excursion, dependant on the position of intervening joints.
Contralateral cervical spine side flexion caused 0.2% increase in median nerve strain in the forearm and 0.8mm and 1.3mm excursion of the nerve in the forearm and upper arm respectively when the shoulder was placed in 90° abduction; values which all decreased when the shoulder was in a 30° abducted position.

In a later study conducted by Dilley et al. (2007) on the ulnar nerve, the authors demonstrated the theory of convergence yet again. Using ultrasonography to image the nerve in the forearm and upper arm of asymptomatic individuals during various upper limb joint movements, the authors reported how moving the wrist from neutral to 40° extension when the elbow and shoulder were maintained in extension and 90° abduction respectively, resulted in distal excursion of the ulnar nerve in both the distal and proximal forearm (2.1mm and 1.1mm respectively). Significantly less movement was evident in the proximal segment of the ulnar nerve with wrist movement than its distal counterpart (p<0.05); findings similar to that of Dilley’s earlier work (Dilley et al., 2003). Maintaining the shoulder at 90° abduction and wrist in neutral, when the elbow was moved from extension (0°) to 90° flexion, proximal excursion of the ulnar nerve in the distal forearm was observed (mean = 0.8mm), with distal excursion of the nerve being evident in the proximal upper arm (mean = 0.1mm); findings demonstrating the theory of convergence.

The effect a moving joint has on nerve segments, not only in closest proximity to that joint, during a neurodynamic test is an important factor clinicians
should be aware of when using these tests as diagnostic or treatment tools. In a patient with a suspected proximal nerve lesion, it may not be considered wise to have the moving joint being located extremely distal to the lesion as the nerve is not being placed under significant strain to determine its sensitivity to movement. For example, viewing Table 1.1 presented by Coppieters et al. (2006a), moving the ankle joint in isolation for a suspected sciatic nerve injury in the gluteal area, will not sufficiently assess the mechanosensitivity of the nerve to movement as no significant movement or strain occurs. However, the addition of hip flexion to ankle dorsi-flexion and knee extension does induce the greatest movement and strain of the sciatic nerve, thereby allowing the nerve’s ability to withstand mechanical stress and movement to be assessed more effectively than if the ankle was moved in isolation.

Whilst the majority of research published in the biomechanical properties of peripheral nerves focus on the elongation of nerves to joint movement (Babbage et al., 2007, Boyd et al., 2005, Coppieters et al., 2006a, Dilley et al., 2003, Dilley et al., 2007) and the concept of convergence, little evidence if available on the relaxation which a nerve undergoes as the nerve bed length is reduced (i.e. divergence). Zoch et al. (1991) reported the median nerve to elongate in extension of the elbow and wrist joint in cadavers, whilst then subsequently shortening as a consequence of elbow flexion. The adaptation of the nerve to the reduced nerve bed length (i.e. elbow flexion) was regarded by Millesi et al. (1990) to occur due to reduced tension in the median nerve, which
occurs at three different levels. Firstly, the main trunk of the nerve adopts a relaxed undulated course whilst the individual fascicles within the nerve trunk also adapt an undulated course. Finally, the individual nerve fibers may also increase their undulated course. These adaptations however, may only occur according to Millesi et al. (1990), if the nerve trunk can move relative to the surrounding tissues, the fascicles can move relative to each other and the nerve fibers can move relative to each other also. The aforementioned authors postulate that a reduction in one of the three levels may be compensated by increased movement at one or both of the other levels. Peripheral nerves must therefore not only be able to tolerate increases in strain and excursion as the nerve bed length is increased, but also have the ability to return to a relaxed, unstressed state upon reduction of the surrounding nerve bed.

It is evident that the median and ulnar nerves in asymptomatic individuals, adapt well to changes in nerve bed length which occur during limb movement (Dilley et al., 2003, Dilley et al., 2007), by ensuring localized strain within the nerve is dissipated along the course of the nerve, thereby preventing damage to the nerve (Butler, 1991). However, the effect different joint movements can have on the magnitude of nerve excursion and strain is a factor which should be taken into consideration for clinicians who use neurodynamic tests in clinical practice. Two different neurodynamic testing techniques, the “tensioning” and “sliding” techniques, have emerged in recent years which are based on the magnitude of
excursion of a nerve and the corresponding strain which occurs during the movements.

The “sliding” technique is one whereby a combination of movements which elongate the nerve bed at one joint, simultaneously reduce nerve bed length at an adjacent joint; the purpose being to produce the greatest range of nerve excursion possible, with the least amount of strain (Coppieters et al., 2009). The opposing technique is the “tensioning” technique which the same authors define as the elongation of the nerve bed at two adjacent joints. It is considered to produce significantly less nerve excursion, but greater strain than the sliding technique (Coppieters et al., 2009). The effect of these two techniques on nerve excursion has been investigated in-vitro and in-vivo by Coppieters and Butler (2008) and Coppieters et al. (2009) respectively.

The in-vitro investigation undertaken by Coppieters and Butler (2008), examined the longitudinal excursion and strain of the median and ulnar nerves at the wrist and proximal elbow during tensioning and sliding techniques in two embalmed cadavers. Despite the small sample size (n=2), the authors reported interesting findings regarding the two neurodynamic techniques. Coppieters and Butler (2008) discovered a sliding technique, specific to the median nerve, to cause twice as much longitudinal excursion of the nerve at the wrist when compared to the tensioning technique (12.6mm and 6.1mm respectively). However, peak strain in the median nerve was substantially less for the sliding
technique (+2.7%) compared to the tensioning manoeuvre (+4.7%). Similarly, the ulnar nerve moved the greatest longitudinal distance with minimal peak strain during a sliding technique (8.3mm; +0.7% respectively) compared to the tensioning method, which caused 3.8mm excursion with corresponding peak strain of +3.2%.

Coppieters and Butler's (2008) findings demonstrated the differing effects sliding and tensioning techniques have on the biomechanical properties of peripheral nerves. The sliding technique, whereby movements were used to decrease and increase the length of the nerve bed simultaneously at adjacent joints, caused the greatest excursion of the median and ulnar nerve, yet with minimal increases in strain. The authors therefore recommend the use of this technique in the treatment of acute neural injuries or post-operatively, as it is a less aggressive manoeuvre compared to the tensioning technique. Coppieters and Butler (2008) advocate the use of both of these techniques to aid healing, suggesting they provide a pumping action or “milking effect” (Rozmaryn et al., 1998) which enhances the dispersal of local inflammatory products surrounding the injured nerve. The actual effect sliding and tensioning techniques have on neural pathologies has yet to be investigated; but their inclusion in the treatment plan for a patient presenting with neural mechanosensitivity should be considered by therapists if the aim is to decrease a nerve's sensitivity to movement.
Expanding on the cadaver study by Coppieters and Butler (2008), the former author, alongside two colleagues, investigated the longitudinal excursion of the median nerve in the upper arm, using ultrasound, in healthy individuals (n=15) for both a tensioning and sliding technique (Coppieters et al., 2009). The sliding technique involved the elbow and neck movements to occur in the same direction at the same time, whilst the tensioning manoeuvre required elbow extension and contralateral cervical lateral flexion to occur simultaneously (Table 1.3).

**Table 1.3: Longitudinal excursion of the median nerve during sliding and tensioning techniques and various joint movements.**

<table>
<thead>
<tr>
<th>Technique</th>
<th>Components of each technique</th>
<th>Mean excursion (mm) + SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sliding</td>
<td>Elbow extension + ipsilateral cervical lateral flexion: moving simultaneously</td>
<td>+10.2±2.8mm</td>
</tr>
<tr>
<td>Technique</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>Elbow moving into extension + the cervical spine maintained in contralateral lateral flexion</td>
<td>+5.6±2.1mm</td>
</tr>
<tr>
<td>Technique</td>
<td></td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>Elbow moving into extension + the cervical spine maintained in ipsilateral lateral flexion</td>
<td>+5.5±2.9mm</td>
</tr>
<tr>
<td>Technique</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>Elbow maintained in extended position + cervical spine moving in a contralateral direction</td>
<td>-3.3±1.3mm</td>
</tr>
<tr>
<td>Technique</td>
<td></td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>Elbow maintained in flexion and cervical spine moving in a contralateral direction</td>
<td>-3.4±0.9mm</td>
</tr>
</tbody>
</table>

"+" denotes distal excursion of the median nerve

"-" denotes proximal excursion of the median nerve.

SD: Standard deviation

Adapted from: Coppieters et al. (2009).
The sliding technique was discovered to produce significantly more excursion than any other technique (10.2±2.8mm; p=0.0001), whilst the tensioning technique had the smallest excursion; a findings which was also statistically significant (1.8±4.0mm; p=0.0001) (Coppieters et al., 2009). Viewing the findings of the isolated joint movement techniques there is minimal difference in the magnitude of nerve excursion between Techniques C and D and Techniques E and F. Whilst a clinical assumption may be that placing one joint in a pre-tensioned position (e.g. Technique C) whilst moving the other joint, will result in decreased longitudinal nerve excursion, these results do not support that concept. When the cervical spine was maintained in contralateral side flexion (i.e. a possible pre-tensioning position) or ipsilateral side flexion (a non pre-tensioning position), no significant difference existed in the extent of median nerve excursion, with an almost identical finding evident between Techniques E and F (Table 1.3). The clinical consequence of such a finding is that assumptions cannot be made by clinicians that by placing one joint in a supposed pre-tensioned position whilst moving the adjacent joint will decrease the extent of nerve excursion and allow for a more aggressive treatment option. It will, according to the evidence presented by Coppieters et al. (2009) have no effect on longitudinal nerve excursion than if the joint was placed in a non pre-loaded position. As a scientific finding, the clinical implications, are such that, if a clinician were to consider trying to “pre-tension” a nerve and use a treatment technique which they may consider to be slightly more aggressive than a sliding technique, it may not have the desired or intended effect.
Coppieters et al. (2009) conclude that understanding the biomechanical effects different neurodynamic techniques have on the nervous system is vital in the implementation of these techniques in clinical practice, yet stress that the findings of their study can really only be applied to the particular segment of median nerve investigated by the authors. It is important to consider what occurs not only distal to the joint being moved but also the nerve segment distal to the subsequent joint according to Coppieters et al. (2009). For example, examination of the median below the elbow and the wrist should be examined during neurodynamic testing, as opposed to just at the elbow, as altered nerve excursion may be evident at remote joints to the examined area.

Based on the findings of the studies discussed previously on longitudinal nerve excursion (Babbage et al., 2007, Boyd et al., 2005, Coppieters et al., 2006a, Coppieters and Butler, 2008, Coppieters et al., 2009, Dilley et al., 2003, Dilley et al., 2007), the clinical assumptions that neurodynamic tests cause excursion and strain of peripheral nerves have been verified. Additionally, the sliding technique has being proven to cause the greatest longitudinal excursion with minimal strain of a nerve compared to the tensioning technique.

As neurodynamic tests assess the mechanosensitivity of the nervous system to movement, in a patient whose condition is easily aggravated by the execution of a neurodynamic test, the selection of treatment should focus on a sliding technique. Whilst this technique not only permits the nerve to move a
greater distance than the tensioning technique, it subjects it to significantly less strain. However, in a patient with a significantly less irritable neural condition, a more aggressive treatment strategy might be considered, whereby the clinician might contemplate utilizing a tensioning technique, to further increase the tolerance of the nervous system to mechanical strain. The importance of conducting research into the area of neurodynamics is vital to ensure a comprehensive understanding exists amongst clinicians as to why they incorporate not only neurodynamic tests into the diagnostic process, but also their choice of specific treatment tools in the neuropathic patient.

Prior to incorporating any test into clinical practice however, it is important to assess its validity quantitatively (Kleinrensink et al., 2000). The subsequent section in this chapter shall therefore discuss the attempts of several authors to validate neurodynamic tests, whilst others prove the reliability of using these tests in clinical practice.
1.2.3 The Validity and Reliability of Neurodynamic Tests

1.2.3.1 Validity of Neurodynamic Tests

Despite their widespread use in undergraduate education and amongst graduates in clinical practice, minimal research has been conducted assessing the validity of neurodynamic tests. Whilst there is no doubt that neurodynamic tests assess both neural and non-neural structures (Coppieters et al., 2005), the structural differentiating component of a neurodynamic test is used to differentiate neural and non-neural components of patient symptoms (Shacklock, 2005). Consequently, the effect structural differentiation has on the neural and non-neural structures or patient symptoms is frequently evaluated by authors assessing the validity of these tests (Lew and Briggs, 1997; Coppieters et al., 2005; 2006b).

Lew and Briggs (1997) investigated the effect of changing the position of the cervical spine during the slump test on pain perception and activity levels of one hamstring muscle in 22 asymptomatic volunteers. Maintaining the pelvis, trunk and lower limb in a fixed position, the latter ensuring hamstring length was constant throughout the test; the authors recorded the activity of biceps femoris and subject pain perception using surface electromyography (EMG) and a Visual Analogue Scale (VAS) respectively. The results firstly demonstrated that cervical flexion during the slump test significantly increases patient symptoms in the
posterior thigh compared to the cervical extension manoeuvre (p<0.001). The EMG readings of biceps femoris were slightly higher during cervical flexion than extension but this difference was not significant (p=0.069). Upon inspection of the EMG results, a large difference is evident between the mean values of the three trials taken for both cervical spine positions (0.95µV). Whilst this difference might appear minute, the EMG actual values presented by Lew and Briggs (1997) for biceps femoris were 2.82 µV and 1.87 µV for cervical extension and flexion respectively, thereby making the difference appears quite substantial. Despite no significant difference being discovered, the potential for Type II error to occur in this study is present, as a visible difference in mean EMG between cervical spine positions does occur, yet the authors state non-significant findings.

Over-all the findings of Lew and Briggs’ (1997) research indicates that the pain alterations which occur during the slump test were not as the result of increased tension within the hamstring muscles, but due to changes in tension within a structure which links the posterior thigh to the cervical spine. Whilst Lew and Briggs (1997) acknowledge a variety of anatomical structures, such as fascia, blood vessels and neural structures could be responsible for these changes; the authors concluded that posterior thigh pain, caused by the cervical flexion during the slump test and relieved by cervical extension, most probably arises from neural structures.
Coppieters et al. (2005; 2006b) utilised a different approach to assess the validity of the slump test, SLR and median nerve neurodynamic tests, choosing an experimental pain model. Whilst it is evident that nerves move as a result of joint movement (Babbage et al., 2007, Boyd et al., 2005, Coppieters et al., 2006a, Dilley et al., 2003, Dilley et al., 2007), the origin of symptoms experienced during neurodynamic tests is ultimately unknown. A pre-requisite for using structural differentiation within a neurodynamic test is that the addition of the manoeuvre will have no effect on pain perception if the pain is of a non-neural origin (Shacklock, 2005b; Coppieters et al., 2005; Coppieters et al., 2006b).

Coppieters et al. (2005) hypothesized that pain perception should remain unaltered when structural differentiation manoeuvres are added to the slump and SLR tests, when the pain is of non-neural origin. To investigate this theory, the aforementioned authors' experimentally-induced muscle pain in healthy individuals, and then subsequently monitored the effect of structural differentiation during the slump and SLR tests on the subjects' perception of pain. The primary finding of the study was that no increase in pain, as measured via Visual Analogue Scales (VAS), was reported with structural differentiation for both neurodynamic tests, despite the pain being of muscular origin. During the progressive stages of the slump test and SLR, a consistent trend in decreasing pain perception was actually observed. However the authors acknowledged this could have occurred due to the dissipation of the intramuscular saline over time. Coppieters et al. (2005) concluded that structural differentiation manoeuvres
utilised during the slump test and SLR has no effect on pain perception when the pain is of a muscular origin.

In a similar study conducted on the upper limb, Coppieters et al. (2006b) also attempted to validate neurodynamic testing for the median nerve using a similar experimental pain model, infusing a bolus of 1.2mL saline (5% NaCl) into the thenar muscles of the hand. Pain perception was recorded over eight different testing positions, each of which was considered to affect the loading of the median nerve to different extents. The eight positions were categorised into two sequences of four manoeuvres, which progressively increased or decreased the loading on the median nerve.

The pain experienced by subjects throughout the entire investigation was located primarily at the site of infusion over the thenar eminence. Slight, but non-significant (p=0.22) increases in pain intensity were reported for the sequences of events during the neurodynamic test which increased loading on the median nerve, with decreases in VAS evident when the nerve bed length was decreased. The findings of this study agree with those previously presented by Coppieters et al. (2005), having also demonstrated that structural differentiation during a neurodynamic test has no effect on experimentally induced muscle pain.
Coppieters et al. (2005) acknowledge that their study was not designed to demonstrate that all symptoms experienced during neurodynamic testing is of neural origin, but merely to contribute to validating these tests. If the findings of both studies (Coppieters et al., 2005; 2006b) had reported significant changes in experimentally induced muscle pain using structural differentiation, then the concept of using structural differentiation in neurodynamic tests would be compromised. The aforementioned studies all suggest that neurodynamic tests are a valuable tool in differentiating pain being of a neural and non-neural origin.

Clinical tests by their nature, can stress tissues and elicit physiological and anatomical responses in any system; muscular, vascular, nervous and articular systems (Balster and Jull, 1997). Whilst neurodynamic tests not only load the nervous system, but also non-neural structures, controversy exists as to the origin of the symptoms elicited during neurodynamic tests (Coppieters et al., 2005). It is ultimately unknown what specific structure elicits symptoms or restricts joint motion during these tests; one proposed candidate for pain reproduction during the slump test is the posterior layer of the lumbar fascia. This anatomical structure attaches into the upper thoracic and tendons of splenius cervicus and capitis superiorly (Barker and Briggs, 1999) and the gluteus maximum and medius inferiorly, whilst the deep lamina of the fascia inserts indirectly into the biceps femoris via the sacrotuberous ligament (Vleeming et al., 1995).
Vleeming et al. (1995) reported that traction testing of the gluteus maximus, gluteus medius and biceps femoris in cadavers elicited the generation of ipsilateral and contralateral tension in the posterior layer of the lumbar fascia. The authors' surmised that the posterior fascial layer acts as a load transmitter between not only the upper and lower limbs, but also between both side of the body and between the abdominal walls and spine. Consequently, Barker and Briggs (1999) suggest the posterior layer of lumbar fascia is eligible to induce symptoms or tension during neurodynamic tests, due to its anatomical connection between the neck, trunk, abdomen, pelvis and upper and lower limbs. However, as Barker and Briggs (1999) admit, the tests conducted by Vleeming et al. (1995) on embalmed cadavers may not reflect the load capacity of these structures in vivo, and therefore the results should be interpreted with caution.

Whilst it is not definitive that the symptoms produced during a neurodynamic test are the result of tension generated within the nervous system, Coppieters et al. (2005; 2006b) contribute to the validation of these test by supporting the use of structural differentiation to distinguish between neural and non-neural oriented symptoms. It may remain an enigma as to what specific structures produce symptoms during the slump test, but considering their widespread use amongst practising clinicians and in third level education, any attempts to validate neurodynamic tests must be commended.
1.2.3.2 Reliability of Neurodynamic Tests

A positive neurodynamic test is constituted by several variables such as a reproduction or alteration in symptoms as a consequence of structural differentiation (Maitland, 1985), the range of motion achieved at the moving joint (Butler and Gifford, 1989, Coppieters et al., 2002), difference in symptom or range of motion responses between limbs (Butler, 2000) or structural differentiation implying the symptoms are of neural origin (Butler, 2000). These measurements are not only important at the initial diagnosis stage, but also during reassessment and following treatment, to determine the effectiveness of treatment modalities. Consequently, the variables typically measured during neurodynamic tests should demonstrate good reliability to warrant their inclusion in clinical examination and reassessment. Several studies have evaluated the inter-tester and intra-tester reliability of various neurodynamic tests’ measurement variables such as onset of pain, sub-maximal pain and maximal pain; reproduction of pain, onset of muscle activity and onset of resistance (Coppieters et al., 2002, Hall et al., 1998, Lew and Briggs, 1997, van der Heide et al., 2001).

Evaluating the intra-tester reliability for examiners accurately detecting onset of resistance (R1) during the Straight Leg Raise (SLR) with various structural differentiation manoeuvres, Hall et al. (1998) reported ICC scores between $r=0.75$ and 0.98; indicating that therapists can have good to excellent
reliability (Coppieters et al., 2002) in detecting R1 during a neurodynamic test, when sessions are conducted 24 hours apart. Intra-session reliability of detecting onset of muscle activity for trapezius, triceps and biceps brachii during an upper limb neurodynamic test (ULNT) with and without structural differentiation ranged from \( r=0.520-0.912 \) in research conducted by van der Heide et al. (2001). The biceps muscle cited the lowest range of ICC scores \( (r=0.520-0.854) \) with trapezius being consistently classified as having moderate/good reliability \( (ICC \text{ range } r=0.605-0.830) \); findings which indicate onset of muscle activity can be reliably determined.

Excellent mean intra-participant reliability \( (ICC=0.98; \ SEM=2.9°) \) when subjects had to determine their onset of pain during an upper limb neurodynamic test with median nerve bias was reported by Coppieters et al. (2002). Similar impressive results were cited for intra-participant reliability \( (\text{mean } ICC = 0.99; \ SEM \text{ of } 1.7°) \) when detecting the onset of sub-maximal pain. Lew and Briggs’ (1997) results were reasonable in comparison to Coppieters et al. (2002), as intra-session reliability for reproduction of pain, via Pearson correlation coefficients were \( r=0.75 \) and 0.78 for the slump test with cervical extension and flexion respectively. When assessing the reliability of asymptomatic subjects in identifying the onset of pain and maximum pain to be tolerated during a neurodynamic test with bias to the median nerve, van der Heide et al. (2001) reported a wide range of reliability, using Intraclass Correlation Coefficients. The reliability of subjects detecting onset of pain \( (P1) \) was excellent during the ULNT.
with the cervical spine in neutral (no structural differentiation) and side flexion (with structural differentiation), evident in ICC scores ranging from r=0.925 to r=0.953. Likewise, when detecting the maximum amount of pain to be tolerated, the subjects were also impressively reliable; with both cervical spine postures (ICC ranges of r=0.881 to r=0.973).

Inter-therapist reliability refers to the reproducibility of a measurement between two or more investigators and is important if confidence is to be placed in the validity of a test (Batterham and George, 2003). Philip et al. (1989) investigated inter-therapist reliability when conducting the slump test in 93 patients who were undergoing treatment for lumbar pain with and without lower limb symptoms. The slump test was regarded as positive if part or all of the patients’ symptoms were reproduced by the slump position and then subsequently decreased with cervical extension. A further factor constituting a positive test was if cervical extension also caused an increase in knee extension range of motion. Using a Cohen’s kappa, the authors reported a high level of agreement (k = 0.89) between therapists when using the reproduction of symptoms as the criteria for a positive test. When increased knee extension was also observed during the slump test, the level of agreement between therapists was still impressive (k = 0.83). These results lead the authors to conclude that the slump test is a reliable clinical test for use between therapists when reproduction of patient symptoms is the criteria for a positive test.
Schmid et al. (2009) cited moderate inter-therapist reliability for an upper limb neurodynamic test (ULNT) for the median, radial and ulnar nerves in a symptomatic cohort. The examiners conducted each neurodynamic test to the point where the patient experienced pain or when end of range was achieved at the moving joint. Using Kappa statistics to evaluate the inter-tester reliability between the two manipulative physiotherapists, the authors reported values of k>0.46, 0.44 and 0.36 for the median, radial and ulnar nerve tests respectively; resulting in Schmid et al. (2009) to regard upper limb neurodynamics tests measured with respect to pain onset and range of motion, to have a moderate reliability.

The inter-tester reliability of experienced manipulative therapists, during a neurodynamic test with median nerve bias, in asymptomatic subjects, with pain and submaximal pain as the outcome variables was evaluated by Coppieters et al. (2002). Inter-tester reliability, as evaluated using ICC, within one session was cited as r=0.96 and r=0.98 for onset of pain and submaximal pain respectively. Inter-examiner reliability between sessions, 48 hours apart, had slightly lower but good reliability for these two outcome variables (onset of pain r=0.86; submaximal pain r=0.89). Coppieters et al. (2002) concluded that with clear operational definitions pertaining to onset of pain and sub maximal pain, in conjunction with good manual handling skills, neurodynamic tests can be reliably used in both a clinical and laboratory setting.
The majority of studies concur that symptom reproduction (Coppieters et al., 2002, Lew and Briggs, 1997, van der Heide et al., 2001), onset of resistance (Hall et al., 1998) and onset of muscle activity (van der Heide et al., 2001) are factors which can all be detected reliably during neurodynamic tests. These are very important findings considering high reliability supports the use of a neurodynamic test during clinical reassessment in addition to assessing the response of a patient to a specific treatment modality. However, the reliability of these variables is always dependent upon the ability of the clinician to conduct and interpret the test; the more reliable the individual between trials and sessions, the less chance there is for error to occur.

As shall be highlighted in the subsequent section (1.2.4), neurodynamic testing elicits a variety of patient responses, which may lead to the diagnosis of neural mechanosensitivity. Should a therapist be unaware of the different responses which are proposed in literature to occur during neurodynamic testing, mis-diagnosis may ensue. A clinician unaware of covert responses could result in an inadequate diagnosis for a patient with subtle neural mechanosensitivity.

Additionally, poor execution of a neurodynamic test may also give a false-negative outcome, such as insufficient thoracic and cervical flexion during the slump test leading to less strain placed on the nervous system and its mechanosensitivity being inadequately assessed. An inconsistent method of conducting neurodynamic tests may also lead to differences in the outcomes.
measured between testing periods. Whilst the explicit level of understanding amongst clinicians as to their level of knowledge or ability in neurodynamic testing has not to date been assessed in literature, these tests, as with all clinical tests, rely on the competency of the practising therapist.

1.2.4 The measurement responses assessed during Neurodynamic Tests

Variable patient responses are assessed during neurodynamic tests, by which clinicians determine whether the test is positive. A reproduction or increase in symptoms which eases with structural differentiation is one response obtained during neurodynamics testing, which Maitland (1985) state is indicative of a positive test. Butler (2000) regards a difference in symptom response between limbs or structural differentiation supporting a neurogenic source as factors which also constitute a positive neurodynamic test. Differences in the achievable range of motion between limbs during a neurodynamic test are also regarded as a positive test by Butler and Gifford (1989) and Coppieters et al. (2002). Each of the aforementioned patient responses do not necessarily occur in isolation and therefore the examining therapist is not limited to viewing the outcomes of a neurodynamic test based on one variable alone.
Pain appears to be a common sensation reported during neurodynamic testing. The majority of subjects in a study conducted by van der Heide et al. (2001) reported experiencing pain during a neurodynamic test for the median nerve with contralateral cervical lateral flexion (CCLF) as the structural differentiating manoeuvre, despite being asymptomatic at the time of testing. The addition of CCLF to the test resulted in 90% of the cohort reporting an increase in sensory symptoms compared to a neutral neck position, with onset of pain occurring an average of 19.2° earlier in elbow extension range during the test.

Balster and Jull (1997) undertook a similar study whereby the authors examined patient response, amongst other factors, during a Brachial Plexus Tension Test (BPTT), also in asymptomatic individuals. Prior to testing, the authors categorised the subjects into two groups according to the range of elbow extension achieved during the BPTT. Group 1 consisted of those with a lack of elbow extension during the test of between 0°-20°, referred to as the “extensible” group whilst those whose lack of elbow extension in the test was >30° were labelled the “less extensible” group. The authors reported no significant difference in level of pain experienced at the elbow extension stage (p=0.553) and CCLF stage (p=0.183) between groups.

Based on the findings of the aforementioned studies, it appears that pain is a typical normative response to upper limb neurodynamic tests, even in healthy individuals. For those clinicians who focus primarily on pain production during
neurodynamic tests, pain can therefore be a misleading variable by which to gauge a test as being positive and negative. Symptom production and reproduction are the most commonly measured variables during neurodynamic tests amongst the clinicians surveyed in Chapter 2 of this thesis (page 95). Whilst provocation of the presenting pain is an important response to assess during neurodynamic testing, perhaps therapists should encompass other variables as suitable measurement tools by which to gauge the mechanosensitivity of the nervous system such as onset of muscle activity or asymmetry in range of motion between limbs.

As the sequences of a neurodynamic test progress, enhanced local muscle activity occurs (Balster and Jull, 1997, van der Heide et al., 2001). The addition of each sequence of the Brachial Plexus Tension test (BPTT) resulted in a corresponding increase in EMG activity of the upper trapezius in all participants in research conducted by Balster and Jull (1997). Significantly greater upper trapezius muscle activity was observed in the less extensible group (i.e. those who had a less elbow extension) than their more mobile counterparts at the following stages within the test; pain onset (p=0.001), the limit of elbow extension (p=0.001) and the limit of CCLF (p=0.006).

Van der Heide et al. (2001) utilised contralateral cervical lateral flexion (CCLF) as the structural differentiating manoeuvre during a neural tissue provocation test with median nerve bias and discovered onset of trapezius
activity to occur $12.2^\circ$ earlier during the range of elbow extension with CCLF compared to a neutral cervical spine position. Boyd et al. (2009) discovered the number of muscles activated between onset of pain (P1) and maximum tolerated pain (P2) increased during the SLR. At P1 during the SLR with plantar flexion, only one muscle was active, yet when then the hip was flexed to P2, six more muscle activated prior to reaching this point. The same finding was discovered when the SLR was conducted using a different ankle position. From these findings, it is apparent that enhanced muscle activity and earlier onset of muscle activity are commonly occurring events during neurodynamic tests with structural differentiation.

Whether an actual relationship exists between muscle activity, pain and resistance experienced during neurodynamic test, has been investigated by numerous authors (Balster and Jull, 1997, Hall et al., 1998, van der Heide et al., 2001). Balster and Jull (1997) reported no significant correlation between EMG activity of the upper trapezius and pain perception levels experienced at the elbow extension and CCLF stages in the more extensible ($r=0.340$) and less extensible ($r=-0.07$) groups for the BPTT. A higher level of upper trapezius muscle activity was however, observed in patients who lacked more than $30^\circ$ elbow extension during the latter stage of the neurodynamic test. It therefore appears that the muscle activity evident during the BPTT did not occur in response to the symptoms experienced.
Van der Heide et al. (2001) however, contradict these findings, reporting moderate correlation ($r=0.751$) between onset (M1) of trapezius activity and onset of pain (P1) when the cervical spine was in a neutral position; a statistical relationship which increased ($r= 0.887$) with CCLF. The onset of trapezius activity occurred on average $13.3^\circ$ earlier in range of elbow extension than P1 during ULNT when the cervical spine was in neutral. Structural differentiation, via CCLF, resulted in M1 within the trapezius occurring only $8^\circ$ earlier than P1. The authors surmised that the onset of activity occurred in response to the onset of pain during ULNT. However, whilst a relationship between M1 and P1 appears to exist in this study, $27\%$ of the cohort had no reporting of pain, yet had the presence of muscle activity within trapezius, a finding which suggests that muscle activity can occur in the response to sensations other than pain during neurodynamic tests.

Investigating slightly different variables than the authors discussed previously, Jaberzadeh et al. (2005) sought to evaluate the motor responses during the elbow extension component of an upper limb neurodynamic test with median nerve bias. The authors regarded increased EMG activity and elbow flexor resistive torque as indicative of increased neural mechanosensitivity; the former being measured using surface electromyography (EMG), whilst the latter was evaluated using a dynamometer. The agonist muscles, also referred to as the experimental muscles, included the trapezius, pectoralis major, biceps brachii, flexor carpi radialis (FCR) and brachialis. The antagonist muscles were deltoid, triceps, infraspinatous and lower trapezius, known as the control
muscles. The experimental muscles were regarded by Jaberzadeh et al. (2005) as those muscles primarily responsible for protecting the median nerve from excessive stretch. Patient onset of pain (P1) and sub-maximal pain (P2) were recorded by a hand-held trigger and before commencement of the test the EMG signals reflected those of relaxed muscles.

An increase in EMG activity following the initiation of the movement to three seconds before P1 was observed, after which point, in all the experimental muscles with the exception of FCR, there was a continuing increase in EMG activity. The activity of the control muscles, excluding triceps, remained minimal throughout. The neutral testing position utilised by Jaberzadeh et al. (2005) caused no change in elbow flexor resistive torque and EMG activity of the experimental muscles, whereas structural differentiation, via contralateral cervical lateral flexion, caused a significant increase in these variables at P1 and P2.

It is possible that the muscular system plays a role in protecting the nervous system from excessive tensile forces as Jaberzadeh et al. (2005) demonstrated the existence of a relationship between pain and muscle activity, whereby with increasing pain, muscle activity increased. Balster and Jull’s findings (1997) demonstrated increased muscle activity in the upper trapezius with the addition of each successive manoeuvre of the BPTT whilst van der Heide et al. (2001) reported trapezius activity to occur earlier during the same
test with structural differentiation than without; all findings which suggest the muscular system may innately protect the nervous system from excessive forces.

In a study investigating the compliance of the lower limb peripheral nerves during the straight leg raise test (SLR) in healthy individuals (n=20), age and sex matched with patients presenting with chronic L5 or S1 radiculopathy (n=20), Hall et al. (1998) utilised two different structural differentiating manoeuvres (ankle dorsi-flexion and cervical flexion). The authors recorded EMG activity of the hip extensors, onset of resistance (R1), range of SLR and Mr (moment of stretched tissue). Moments are regarded by Hall et al. (1998) as a means of describing the forces during the SLR. A moment is calculated by the product of the mass of the leg lifted and its horizontal distance from the pivot point (Hall et al., 1998). Subtracting the moment of the weight of the leg from the moment required to lift the leg, the moment of the stretched tissue is calculated (Mr) (Goeken and Hof, 1994). Mr was regarded by Hall et al. (1998) as representative of the compliance of the lower limb peripheral neural tissue and was measured using a load cell under the ankle orthosis during the SLR.

Hall et al. (1998) cited no significant difference (p=0.07) between the range of SLR achieved for R1 between the groups; likewise for the angle in SLR where Mr first increased (p=0.46). However, altered neural tissue compliance, via significant increases in Mr, occurred following onset of muscle activity in the group of individuals with radiculopathy. Prior to this point, a normal compliance of
the neural system to the SLR was evident. There was no sudden change in Mr, and therefore neural tissue compliance, during the SLR that could be perceived by the examiner as R1, until well into the range of movement when muscle activity occurred. There was however, a significant difference between the range of SLR reported at R1 and Mr in both the control group (p<0.0001) and the patient group (p<0.0001); with Mr occurring lower in range. Onset of muscle activity may therefore be a more appropriate outcome measurement to use when assessing patients with radiculopathy during the SLR as after this point, significant changes in Mr, and therefore neural tissue compliance actually occurs.

As R1 was not detected significantly earlier in range in the patients with radiculopathy, Hall et al. (1998) suggest that using this variable to determine neural dysfunction is inappropriate in this population. The authors therefore support the use of onset of muscle activity as a diagnostic tool in patients with suspected radiculopathy; a suggestion which would be difficult to advocate to clinicians, considering the cost of EMG equipment and software, training costs and the reliability of the clinician using the equipment. Despite presenting interesting results, the realism of implementing Hall et al.’s (1998) suggestion of clinicians assessing M1 during neurodynamic tests, is unlikely.

Following the onset of activity of the hamstring muscles during the SLR, a significantly higher Mr value was observed in the patient group than their healthy counterparts (p=0.01) in Hall et al’s (1998) study; a finding which was not evident
prior to M1. These results lead to authors to theorise that the hamstring muscles have a protective influence on the nervous system during the SLR. Hu et al. (1995) states that the nervous system can become sensitive to the mechanical forces exerted during a neurodynamic test resulting in a protective muscular contraction response; hence the increase in muscle activity discovered by Balster and Jull (1997) and van der Heide et al. (2001) during upper limb tests. Clinicians should be aware that increased activity of a muscle during a neurodynamic test may be occurring in response to the actual test itself and not due to an injury within the muscle itself.

Little is known about how muscle, resistance and pain onsets relate to each other during neurodynamic tests. Should muscle activity onset occur at the same instance as pain or symptom onset, an assumption could be made that the former occurred in response to the latter. Alternatively, should muscle activity occur significantly earlier in a neurodynamic test than a patient’s reporting of pain onset, then muscle activation appears to occur independent of symptoms. In a hamstring injured population, it is unknown what type of relationship exists between muscle activity of the hamstrings, symptom occurrence and the resistance experienced by the clinician conducting the slump test. Considering Turl and George (1998) ascertain that neural mechanosensitivity, as determined via the slump test, is present in hamstring injured athletes, it is an ambiguous association which has emerged from a study of limited subject numbers (n=14) of whom just over half the cohort actually had a positive slump test. Nonetheless, as
will be discussed in the following section, the potential of a positive slump test, and therefore neural mechanosensitivity, co-existing with hamstring injury is feasible, due to the intimate neuromuscular relationship of the sciatic nerve and the hamstring muscle group in conjunction with the remote lumbar spine.

1.2.5 Hamstring Injury

1.2.5.1 Epidemiology of Hamstring injury

Over three-quarters (78%) of injuries in professional English football lead to a minimum of one match missed and a mean 24.2 days lost per injury (Hawkins et al., 2001). The lower extremity is the most vulnerable site of injury in professional soccer and Australian Football, accounting for over 85% of total injuries (Hawkins and Fuller, 1999, Hawkins et al., 2001, Walden et al., 2005) of which the thigh is the most commonly injured body part (Orchard and Seward, 2002) accountable for 16% of all injuries (Walden et al., 2005). Muscular strains are the most frequent type of injury to the thigh (Hawkins and Fuller, 1999, Orchard and Seward, 2002), with injury to the posterior thigh being significantly more common than the anterior thigh (p<0.01) (Hawkins and Fuller, 1999, Hawkins et al., 2001, Walden et al., 2005).

Consisting primarily of the hamstring muscles, a muscle group which has the highest rate of injury in the Australian Football League (AFL) and soccer
it is unsurprising that posterior thigh injury (PTI) dominates injury rates within sport (Hawkins and Fuller, 1999, Hawkins et al., 2001, Walden et al., 2005). Hamstring injuries account for 12-15% of total injuries in professional soccer and Australian football (Orchard and Seward, 2002, Woods et al., 2004), in addition to having the highest recurrence rate of all other injuries (Orchard and Seward, 2002) approximating to 12% (Woods et al., 2004). Considering re-injury to this muscle group is more severe than initial injury in terms of missed days training (25.1 days versus 19.1 days; p<0.01) (Hawkins et al., 2001), coupled with the high susceptibility to re-injury (Woods et al., 2004), injury to the hamstring or posterior thigh region is of primary concern to clinicians and athletes.

The diagnosis of hamstring injury is typically made via clinical means with controversy existing in several cases, particularly in minor strains, as to whether a muscle strain is the actual cause of the symptoms experienced in the posterior thigh (Verrall et al., 2001). Almost one-third (31%) of AFL players were reported by Schneider-Kolsky et al. (2006), to have an absence of local muscular pathology on MRI scan, despite being clinically diagnosed with a hamstring strain; a finding regarded by Verrall et al. (2001) as indicative of referred pain as a consequence of lumbar spine or neural disorders. A posterior thigh injury is regarded for the purpose of this thesis as an injury whereby the patient reports pain in the posterior thigh (Verrall et al., 2001) with concomitant weakness of the hamstring muscles upon isometric contraction, decreased range of motion via the
straight leg raise test with the ankle in neutral and finally, pain in the posterior thigh upon palpation (Heiderscheit et al., 2005).

1.2.5.2 Predictive risk factors for Hamstring injury occurrence

The ability to identify athletes susceptible to hamstring injury would allow appropriate management strategies to be applied which may subsequently decrease the incidence rate of injury and re-injury to this muscle group. Numerous authors have focussed on attempting to identify the risk factors which may pre-determine those athletes most susceptible to hamstring injury (Arnason et al., 2004, Bennell et al., 1998, Cameron et al., 2003, Gabbe et al., 2005, Hagglund et al., 2006, Orchard, 2001, Verrall et al., 2001). A huge variability of results have been cited, from an array of sporting disciplines, with little consensus achieved on the predictive factors for injury to this muscle group.

Factors such as a history of previous injury to the knee or pubis (Verrall et al., 2001), hamstring strength (Cameron et al., 2003), quadriceps flexibility (Gabbe et al., 2005) and ethnicity (Verrall et al., 2001) are just a few proposed predictive risk factors for hamstring strain. The only two factors however, which appear to achieve consensus in literature regarding identifying hamstring injury prior to its occurrence are; advancing age (Arnason et al., 2004, Gabbe et al., 2005, Hagglund et al., 2006, Orchard, 2001, Verrall et al., 2001) and previous

Utilising the data obtained prospectively from an injury surveillance system (Australian Football League (AFL) Injury Surveillance system) between 1992 and 1999, Orchard et al. (2001) discovered intrinsic factors, such as age, height, weight and ethnicity to be more predictive of muscle strain than extrinsic ones (e.g. wind speed and temperature), confirming that having a history of injury to a muscle group is the most important risk factor to re-injury of the same muscle. Therefore, athletes who sustain an initial hamstring injury are innately more at risk of injuring the same muscle group than those who have never suffered from this injury. Additionally, the authors reported that having a history of calf muscle injury to be predictive of injury to the hamstrings, whilst advancing age was reported as a risk factor for both hamstring and calf strains.

Verrall et al. (2001) concurred with Orchard’s (2001) findings of advancing age increasing the risk of sustaining a posterior thigh injury (PTI) having prospectively investigated 114 AFL and South Australian National Football League (SANFL) players, recording via interview, the age, height, weight, ethnicity and history of previous injuries. Over a quarter (28%; n=32) of all players sustained a PTI and those athletes of older age, aboriginal descent, with
a history of PTI or knee injury, were found to be at significant risk \( (p<0.01) \) of hamstring injury.

In another prospective study conducted on 126 community level AFL players, musculoskeletal screening tests and a questionnaire were utilised by Gabbe et al. (2005) in attempting to predict hamstring injury susceptibility. A total of 26 hamstring injuries were reported in 20 players and the results indicated that decreased quadriceps flexibility and age were significant predictors of hamstring injury in the cohort. Evaluating other potential risk factors such as age, range of motion, power, jumping ability and peak oxygen uptake, to name but a few, in professional male football players, Arnason et al. (2004) identified history of previous injury and age as the only two predictors of hamstring strains. Likewise, Bennell et al. (1998), having evaluated the strength of the quadriceps and hamstring muscles groups, via isokinetic testing, in 102 male professional and amateur AFL players, reported 11.8% \((12/102)\) of the cohort sustaining a hamstring injury with the primary finding of the study being, that a history of hamstring injury increased the risk of re-injury.

What is evident from the research presented to date on predictive factors for hamstring injury is that achieving consensus amongst authors on these actual variables is inherently difficult. It is notable that the majority of the aforementioned research was predominantly conducted in the Southern Hemisphere on AFL players. These results can be extrapolated to professional
and semi-professional sports within the U.K. such as rugby league, rugby union and football, as Australian Rules is very similar in nature and format to the aforementioned sports.

A potential flaw in several of the studies evaluating risk factors for hamstring injury is the inherent reliance on the diagnostic capabilities of the medical staff at the participating teams. The diagnosis of hamstring injury was generally made clinically, with no intrinsic investigation, such as Magnetic Resonance Imaging (MRI) or ultrasound, to verify the diagnosis. The only authors who utilised radiological investigations as part of the physical examination in their population were Bennell et al. (1998); albeit only just over half of their injured cohort (57%) underwent this investigation. Bearing in mind the findings of Verrall et al. (2001) and Schneider-Kolsky et al. (2006), whereby 18.75% and 31% of AFL players respectively, who presented clinically with a posterior thigh injury, had no evidence of local muscular pathology on MRI scan, radiological investigations may be warranted in the posterior thigh injured athlete. However, in this authors opinion, MRI and ultrasound are not frequently utilised tools for diagnosing hamstring strains in the U.K., particularly amongst semi-professional athletes and on occasion professional elite sportspeople. Gough-Palmer et al. (2009) reported the majority of MRI scans requested by General Practitioners (GPs) over a 12 year period involved injuries sustained to the brain, spine and knee. It is therefore unlikely that athletes with posterior thigh pain will undergo
MRI or ultrasound scanning, unless they compete at such a level whereby their respective clubs have their own private investigatory equipment.

1.2.5.3 Previous Hamstring injury as a risk factor for subsequent hamstring injury

The previously discussed research pertaining to risk factors and hamstring injury all concur that as players advance in age, their susceptibility to hamstring injury increases significantly; whilst those with a history of this injury are vulnerable to re-injury (Arnason et al., 2004, Gabbe et al., 2005, Hagglund et al., 2006, Orchard, 2001, Verrall et al., 2001). Hagglund et al. (2006) reported how sustaining an injury to the hamstring, groin or knee joint, can result in a two to four fold increase in risk of an identical injury to the same leg, whilst Bennell et al. (1998) agrees in terms of hamstring injury, having provided evidence that AFL players with a history of this injury are 2.1 times more likely to sustain another hamstring injury than those who had no prior injury to the muscle group. Verrall et al. (2001) cites athletes with a history of PTI being 4.9 times at increased risk of hamstring strain than those without. In the study conducted by Bennell et al. (1998) a significantly larger percentage of players who sustained a hamstring injury during the study, reported having a history of hamstring strain (66%), compared to the non-injured group (31%) (p=0.02).
The reasoning as to why previous hamstring injury has such a pronounced effect on re-injury rates to this muscle group is speculative with numerous variables suspected, such as inadequate rehabilitation or returning to competition too soon. Due to variations in the type and severity of injury, differences in treatment strategies by clinicians and the variability of rehabilitation programmes undertaken in the treatment of hamstring injuries, it is inherently difficult to ascertain the exact cause as to why hamstring injuries recur. With global variations in the treatment of hamstring injuries, it is doubtful a specific factor will ever be discovered as to why sustaining a hamstring injury makes an athlete significantly more vulnerable to re-injury of this muscle group. A history of posterior thigh injury is an irreversible risk factor for hamstring injury and one which clinicians cannot erase or modify. Whilst flexibility or strength of a muscle can be addressed to potentially minimise risk of hamstring injury and recurrence, previous medical history and age are two factors a clinician cannot manipulate.
1.2.5.4 Age as a predictive risk factor for Hamstring injury

It appears that the older an athlete is, the more at risk they are of sustaining a hamstring muscle strain (Arnason et al., 2004, Gabbe et al., 2005, Hagglund et al., 2006, Orchard, 2001, Verrall et al., 2001). Players over 23 years of age are almost four times more likely to fall prey to a hamstring strain than those younger than 23 years (Gabbe et al., 2005). Verrall et al. (2001) stated that increasing in age by one year can increase the likelihood of hamstring injury by 1.3 times, independent of a past history of PTI. Arnason et al. (2004) found similar results; the oldest group of players in their cohort were at a significantly higher risk of hamstring injury than the intermediate age group.

Demographics presented by Orchard et al. (2004) in Figure1.3, highlight the increasing prevalence of hamstring injuries in male athletes with advancing age; a trend which is not as pronounced in any of the other anatomical structures presented. Despite the age span being relatively limited in the findings of Orchard et al. (2004) (from <21 years to 30+ years), the trend of hamstring injury prevalence increasing with advancing age is apparent. Injury to the calf muscle group is the only other soft tissue to demonstrate a continuous increase in injury occurrence with advancing age.
adapted from Orchard et al. (2004).

Figure 1.3: Injury prevalence (shown in terms of missed games per season) by player age in the Australian Football League (AFL).

It is unclear as to why the ageing process has such a detrimental effect on the integrity of the hamstrings in athletes (Orchard et al., 2004). However, a very plausible, but unverified theory suggested by Orchard et al. (2004) is that hamstring injury occurs as a consequence of lumbar spine degeneration, which in turn is a natural by-product of the ageing process. In research conducted by
Burnett et al. (1996) and Ong et al. (2003), the intervertebral disc at L5/S1 level suffers from the most degeneration of all the other lumbar discs. Referring back to Figure 1.3, if these results are viewed from the point of view of the levels of the lumbar spine which innervate the structures presented in the graph, it is those structures which are innervated by L5/S1 nerve roots (i.e. hamstring and calf muscles) that have this increasing trend of injury with advancing age. Consequently, an assumption which has arisen in literature over recent years is that hamstring injury occurrence and recurrence arises due to degenerative changes within the lumbar spine; two events which occur with advancing age. It is evident from Orchard et al’s (2004) findings (Figure 1.3), that injury to the structures innervated by L5/S1 (i.e. hamstring and calf muscles) has a direct correlation with advancing age. Whether this relationship continues beyond the age range used in the above study (30+ years) is unknown and may warrant further investigation.

It is of interest that two pathological events, hamstring strains and lumbar spine degeneration, both increase in prevalence with advancing age. The subsequent section of this chapter will explore this enigmatic relationship and attempt to provide an insight as to how degeneration of the intervertebral discs in the lumbar spine can ultimately cause injury to the hamstring muscles.
1.2.5.5 The Lumbar Spine and Hamstring Injury

Spinal degeneration, despite occurring with advancing age, does not limit itself to the elderly (Niosi and Oxland, 2004). Sports participation is regarded by Bono (2004) as a risk factor for the development of disc degeneration, evident in the findings of Elliott et al. (1993) whereby 21% (5/24) of young male fast cricket bowlers exhibited abnormal MRI scans of the lumbar spine at the average age of 13.7 years. In an alternate study, four of 19 fast bowlers (21%) (mean age 13.6 years) demonstrated disc degeneration on MRI scan; a statistic which increased in the same population 2.7 years later where a further seven bowlers (37% entire cohort) were found to have degenerative lumbar discs (Burnett et al., 1996). The increase in prevalence of disc degeneration between testing sessions was found to be significant (p=0.008) by the authors, as was the incidence of back pain (5% and 53% respectively; p=0.002). However, no significant correlation was found between the incidence of back pain and the prevalence of disc degeneration in the retest session. The aforementioned studies demonstrate that disc degeneration is not just limited to the elderly, being present in athletes as young as 13 years of age.

Whilst the actual cause of disc degeneration is unknown (Ong et al., 2003), the majority of degenerative changes generally appear to occur at the more caudal levels of the lumbar spine, in particular L5/S1 (Hangai et al., 2008, Ong et al., 2003). Hangai et al. (2008) reported aging to substantially correlate...
with disc degeneration at all levels of the lumbar spine, with sports participation being specifically correlated with degeneration of the L5/S1 disc. In the previously mentioned study by Burnett et al. (1996), L5/S1 was the lumbar level with the highest incidence of disc degeneration at both initial test and retest in the young cricketers.

During the 2000 Olympic Games, Ong et al. (2003) conducted MRI scans on 31 athletes' lumbar spines who presented with low back pain, with or without sciatica. Disc displacement, height and signal intensity of the lumbar spine (L1/2 to L5/S1) were examined to determine the presence and extent of disc degeneration. The authors discovered a variety of radiological abnormalities within the cohort; over half the entire cohort (58%) showed evidence of disc displacement at one or more levels in the lumbar spine, with the greatest number of displacements evident at the L5/S1 level. Conversely, at L1/L2 and L2/3 levels, there was no evidence of any disc displacement. A similar trend was observed for disc height whereby reduced disc height was most prevalent at L5/S1 level, whilst L1/L2 had no abnormalities for this variable in any athlete. Reduced signal intensity was also most common in the L5/S1 discs, with Grade 3 degeneration being the most prominent at this level. Just over a third (38%) of the population had a normal radiograph for signal intensity at L5/S1 level whilst only four athletes had a normal disc signal intensity at all lumbar levels.
Ong et al. (2003) demonstrated that disc degeneration is highly prevalent in elite athletes, with the L5/S1 disc being the most vulnerable to degenerative changes. The primary limitation of the study by Ong et al. (2003) was the lack of a control group and therefore no statistical analysis or comparisons were undertaken. Also, the authors had no information pertaining to symptoms the athletes were presenting with or whether they were susceptible to recurrent episodes of low back pain.

Athletes not only have more degenerative changes to the intervertebral discs than the normal population (Sward et al., 1991) but also the more caudal the disc in the lumbar spine, the more vulnerable it is to degenerative changes. The findings of Burnett et al’s (1996) study are very concerning considering the young age of the population investigated. Presenting degenerative changes in adolescent bowlers is an alarming finding as several of those athletes had initial signs of degeneration from 13 years of age. Considering the incidence of lumbar spine degeneration increases with advancing age, alongside the fact this condition is evident in adolescent athletes, it is unsurprising the prevalence of lumbar spine degeneration is significantly higher in athletes than their non-sporting counterparts. The consequences of having a higher incidence of disc degeneration are unknown; yet it has been theorised that hamstring injury occurrence is one such consequence (Orchard et al., 2004).
Disc degeneration according to Niosi and Oxland (2004) can have an indirect effect on the ability of the spine to protect the neural elements. The collapse of a disc can occur as a consequence of degeneration thereby causing increased weight bearing of the facet joints of the adjoining vertebrae and subsequent impingement of the nerve root at the collapsed level (Haig, 2002). Orchard (2001) and Orchard et al. (2004) postulate that impingement of the L5/S1 nerve root occurs as a bi-product of lumbar spine degeneration; the effect being hamstring and calf muscle fiber denervation and overall decreased muscle strength.

In a study evaluating the effect of denervation on muscle, D'Albis et al. (1995) reported that in the Type II fiber dominated gastrocnemius muscle in rabbits, the maximum shortening velocity and twitch contraction time following denervation represented those of a slow-twitch muscle. The authors demonstrated that the response of the gastrocnemius muscle to denervation was a progressive atrophy of fast-twitch fibers and hypertrophy of slow-twitch fibers. The findings of d'Albis et al. (1995), despite being on animals, have the potential to occur in the hamstring muscle group, as these muscles are composed primarily of Type II muscle fibers (Garrett et al., 1984). Denervation of the hamstring muscles, could result in the atrophy of Type II fibers, leading to an overall change in the function of the muscles, to represent that of a slow twitch muscle. Lacking the ability to rapidly contract, particularly eccentrically, during
sporting activities as a result of Type II muscle fiber atrophy would increase the susceptibility of the hamstrings to injury.

An indirect relationship appears to exist between lumbar spine disc degeneration and hamstring injury occurrence. As a consequence of degeneration of the disc at L5/S1, the nerve root which supplies the hamstring muscles can in time, cause denervation of these muscles, altering their contractile characteristics, thereby rendering this muscle group vulnerable to injury. This relationship between disc degeneration, specifically at the L5/S1 level, and hamstring injury, is speculative, but its feasibility cannot be ignored.

Progressive disc degeneration not only affects the integrity of the nerve root at the affected spinal level, but also has consequences for the mobility of the spine and has been associated with hypomobility and hypermobility of the vertebrae (Andersson et al., 2006). Disc degeneration leads to tears of the annulus of the disc (Haig, 2002, Tanaka et al., 2001) and it has been hypothesised that a painful or unstable spine can result (Tanaka et al., 2001). Over time, with ever increasing reduced disc height, facet joint hypertrophy can occur as a consequence of increased pressure placed on these joints, leading to increased spinal stiffness (Haig, 2002). The relationship between spinal kinematics and disc degeneration is unknown (Tanaka et al., 2001), yet the possibility exists that abnormal vertebral movement occurs as a consequence of spinal degeneration.
Assessment of intervertebral mobility is an integral part of the musculoskeletal examination in a clinical setting and is traditionally undertaken using spinal accessory movements (Binkley et al., 1995), which aims to assist clinicians in detecting not only the symptomatic spinal level, but also the behaviour of pain relative to range of motion (ROM) and the presence of muscle spasm. Accessory motion testing is performed to establish segmental stiffness, which is typically categorised as hypomobile, normal or hypermobile (Binkley et al., 1995). As hypermobility and hypomobility have both been suggested to occur as a consequence of disc degeneration (Andersson et al., 2006), there lies the potential that either one of these mobility abnormalities exist in the lumbar spine of athletes with hamstring injuries.

With L5/S1 level suffering from the greatest disc degenerative changes in athletes, it is plausible that abnormalities in these segmental spinal movements will be identified on accessory motion testing. As an apparent relationship appears to exist between lumbar spine degeneration and hamstring injuries, it is also feasible that hamstring injured athletes may also present with hypermobility or hypomobility of the lumbar spine. No research to date has evaluated the mobility of the lumbar spinal vertebrae in athletes with PTI, irrespective of whether the athlete actually reports low back pain. Investigation into this area could add more understanding to the ambiguous relationship which appears to exist between the lumbar spine and hamstring injury. Considering "back related hamstring injury" is a concept which has been uttered in research (Orchard et al.,
2004, Schneider-Kolsky et al., 2006, Verrall et al., 2001), it is important to establish whether abnormalities within the lumbar spine co-exist with hamstring injury.

1.2.5.6 Age, Disc Degeneration and Hamstring Injury

It is interesting that the muscle group most injured in football, rugby union and AFL is innervated by the nerve exiting at a level of the lumbar spine which suffers from the most degenerative changes of all the levels of the spine in athletes. The fact the prevalence of hamstring injury and L5/S1 disc degeneration both increase with advancing age is another factor which suggests a strong relationship exists between these variables. It is worth noting that whilst the assumption may be that disc degeneration and back pain co-exist (Niosi and Oxland, 2004), this is not necessarily the case as there are individuals who present with intervertebral degenerative changes, but who remain asymptomatic (Maitland, 2005).

It is possible that in athletes with evidence of disc degeneration absent of back pain, who present with posterior thigh pain, with no local muscle injury, may actually have a false-positive hamstring strain as a result of subtle damage to the sciatic nerve as an overall consequence of L5/S1 disc degeneration. Determining the existence of lumbar spine abnormalities in a clinical setting, without the use of radiological interventions, is typically undertaken using spinal accessory motions,
whilst assessment of the sciatic nerve is typically undertaken using neurodynamic testing. Whilst there are more invasive, quantitative methods in which to assess lumbar spine abnormalities and nerve injury, these are options not readily available to the clinician treating a posterior thigh injured athlete in non-professional sports. In more severe, prolonged or aggravated pathologies, these diagnostic tools, such as nerve conduction tests or MRI scans, may be warranted in the diagnostic process. However, for a clinician who works in a sports setting, continually referring athletes who present with lumbar or lower limb symptoms for intrinsic examinations is not a realistic option. Consequently, primitive clinical assessment tools have been advocated for use in determining lumbar spine and peripheral nerve abnormalities, such as spinal accessory motions and neurodynamic testing respectively.

The slump test is regarded as a vital diagnostic tool for patients with suspected hamstring strain (Turl and George, 1998) and has been advocated as an accelerant for recovery from this injury (Kornberg and Lew, 1989). Despite these statements and its frequent use in clinical settings and the undergraduate curriculum for physiotherapists and sports rehabilitators in the U.K. (section 2.4; page 95), the slump test is a very under-researched diagnostic test.
1.2.6 The slump test and posterior thigh injury

A posterior thigh injury (PTI) does not automatically infer injury to the hamstring musculature (Woods et al., 2004) as evident in the findings of Verrall et al. (2001) who reported almost 20% (18.75%; 6 of 32 players) of AFL players with a PTI having a normal MRI scan of the hamstrings, whereby local isolated pathology was absent. Schneider-Kolsky et al. (2006) discovered a higher incidence with 31% (18 players from a total of 58) of hamstring injured AFL players having an absence of muscle damage on MRI scan despite being diagnosed clinically with a hamstring muscle strain. Butler (1991) therefore advocates that mechanosensitivity of the neural system should be suspected in patients presenting with any or all of the following: an apparent hamstring injury with an absence of bruising, a painful spot which is difficult to palpate, an ambiguous mechanism of injury or whereby the patient complains of spinal pain.

Whilst the slump test cannot eliminate the presence of muscle damage in athletes with suspected hamstring strain, its role is to determine if there is a neural involvement in the injury or re-injury of this muscle group. Turl and George (1998) evaluated the slump test in 14 rugby union players, of varying playing positions, who suffered from recurrent Grade I hamstring strains, reporting a positive slump test in 57% of the cohort. The criterion used by the authors to constitute a positive slump test was that the original hamstring pain would be reproduced with cervical flexion, and subsequently alleviated by cervical extension. However, considering the cohort were asymptomatic for a minimum of
four weeks before testing, a degree of inaccuracy could be present, as the testers were relying on patient recall for the purpose of diagnosing a positive slump test. Also worth noting, is that the average time from the last occurrence of hamstring injury in those players with a positive slump test was two months, whereas in those with a negative slump test, this time period was two weeks longer. It is possible that in the latter group, further resolution of any neural mechanosensitivity could have occurred in that time span, particularly if these players undertook any form of neural mobilisations as a treatment strategy.

Nonetheless, Turl and George (1998) concluded that mechanosensitivity of the sciatic nerve was the cause of pain within the cohort with a positive slump test and that it possesses the ability to mimic Grade I hamstring muscle strains. The intimate anatomical relationship between the sciatic nerve and hamstring muscles has the potential to play a significant role in the occurrence or recurrence of this injury. Repeated injury to the hamstring muscles may produce inflammation and possible scarring within the muscle (Shacklock, 2005a); factors which, according to Shacklock (2005a) can interfere with the mobility of the sciatic nerve. Resultant fibrosis, lesions or intramuscular adhesions following muscle injury can reduce, in accordance with Turl and George (1998), the mobility of a nerve; and thereby lead to secondary nerve damage. It is unknown at what particular stage during the healing process that scar formation can interfere with sciatic nerve movement, or to what extent a person must remain
immobile for nerve mobility to become compromised, but the above authors infer this occurrence is a possibility.

The suggestion by Turl and George (1998) and Shacklock (2005a) that muscular damage to the hamstrings, particularly of Grade 1 nature, has the ability to significantly alter the movement of the sciatic nerve is questionable. Considering the size of the sciatic nerve relative to the bulky hamstring musculature, the likelihood of muscle damage and subsequent scar tissue formation as a consequence of Grade 1 strain, occurring directly over the sciatic nerve and therefore “tethering” the nerve is a dubious concept. There may be a possibility that with substantial bleeding within the muscle, that indirect compression of the nerve occurs thereby potentially reducing neural mobility, but excessive haemorrhage is not a factor typically associated with Grade 1 injury. Ultimately, it is unknown what effect hamstring muscle injury has on the mobility of the sciatic nerve in the posterior thigh.

Despite the majority of hamstring injured players (57%) in Turl and George’s (1998) study having a positive slump test, thereby suggesting there was a neural involvement in the players’ symptom production, no intrinsic investigation examining the excursion of the sciatic nerve in athletes with a supposed hamstring strain has ever been undertaken. The majority of research examining nerve excursion in-vivo during neurodynamic tests focus on the peripheral nerves in the upper arm (Dilley et al., 2003; Dilley et al., 2007; Hough
et al., 2007; Coppieters et al., 2009). Whether this is due to the manual ease in which upper limb tests can be conducted compared to the rather cumbersome slump test, is unknown. Discovering whether hamstring injury affects the excursion of the sciatic nerve would play a role in a clinician’s treatment plan, in that, if excursion was reduced, appropriate neurodynamic techniques, such as sliding manoeuvres, could be incorporated into the treatment plan to improve the nerve’s sensitivity to movement and strain.

As the slump test in-vivo involves many gross movements for both the patient and clinician to conduct, such as knee extension with cervical and thoracic flexion, it can be a daunting test to undertake in research, as the quality of the execution of the test may be compromised. Nonetheless, Ellis et al. (2008) cited good reliability when assessing the movement of the sciatic nerve in the posterior thigh during a sliding technique of the slump test. In-vitro, the slump test has been investigated in previous research (Inman and Saunders, 1942, Falconer et al., 1947, Smith, 1956); albeit the cadavers may not necessarily have been placed in a full slump position (Smith, 1956). The findings of these studies nonetheless provide invaluable insight into the response of the spinal cord and peripheral nervous system to joint movement, demonstrating that trunk flexion and hip flexion cause movement of different spinal nerves, dependant on which joint is moving. Whilst these findings can be extrapolated to in-vivo scenarios regarding the slump test, the practicality of using cadavers, particularly unembalmed specimens, is questionable as the researcher would be placed
under substantial time pressure to ensure reliable measurements are obtained in addition to the risk of infectious disease being high (Kleinrensink et al., 1995). Despite this however, the aforementioned authors reported little difference to exist in peripheral nerve tension between embalmed and unembalmed bodies.

The implications of research focussing on the upper limb, is the inability to directly apply the findings to the lower extremity and its peripheral nerves. There is no upper limb test which mirrors that of the slump test, as the latter typically incorporates the entire spine and lower limb into the test, whilst upper limb tests are relatively discrete tests whereby only the arms, shoulder girdle and cervical spine are primarily utilised. Additionally, there is no acute muscular injury of the upper limb which has such an intriguing relationship with its surrounding peripheral nerves, such as that of the hamstring muscle group and sciatic nerve. The hamstring muscles have a very different relationship with sciatic nerve compared to upper limb muscles, as the former has two different nerve supplies (tibial and peroneal nerves) due to having two-heads, whilst similar muscles in the upper limb, such as biceps brachii, which also has two heads, has innervation by the musculocutaneous nerve (Izzi et al., 2001). The most common neuropathies which occur in the upper limb are chronic in nature, such as carpal tunnel syndrome or thoracic outlet syndrome with acute neural injuries only evident following significant trauma such as anterior shoulder dislocation (Izzi et al., 2001). Overall, whilst those studies conducted on the upper limb significantly contribute to an understanding of neurodynamic tests, the extrapolation of their
findings to the slump test is difficult; therefore this is an area which requires further research.

The central theme throughout this research is the slump test, in athletes with clinically diagnosed hamstring strains. Despite being advocated as a useful diagnostic and treatment tool in patients with spinal pain and upper and lower limb symptoms (Shacklock, 2005a) it is a neurodynamic test relatively under-researched. Whilst research into neurodynamics has evolved greatly in the past decade lead by Michel Coppieters and David Butler in Australia and Andrew Dilley, Alan Hough and Jane Greening in the U.K., the slump test has not been in the forefront of these investigations. Only a few clinical studies have evaluated the slump test and its relationship with hamstring injury; yet none to date have investigated this neurodynamic test at a deeper, intrinsic level in this particular cohort. The slump test therefore forms the nucleus of this research project and the primary studies within this project have been developed around this neurodynamic test, with an aim at probing deeper into the muscular and neural events which occur during this test. The target population throughout this thesis are athletes with hamstring injury; chosen due to the ambiguous relationship which appears to exist between this injury and neural mechanosensitivity.
1.2 Aims and Objectives

To further understand the slump test and its relationship with hamstring injury, three core studies were undertaken in this research project, with two further sub-studies conducted. The initial study (Study 1) sought to examine the slump test as a predictive risk factor for hamstring injury, the findings of which, lead to the author of this thesis seeking to investigate the slump test in substantially more detail. Consequently, Study 2 examined muscle, pain and resistance onsets during the slump test in athletes with a clinically diagnosed hamstring strain. Following from this study, Study 3 was developed with the intention of examining the slump test at an even more intrinsic level; whereby ultrasonography permitted the quantification of the longitudinal excursion of the sciatic nerve during the slump test in athletes with posterior thigh pain. Two additional sub-studies were undertaken during this thesis; one assessing the vertebral mobility of the lumbar spine in athletes with a clinically diagnosed hamstring strain, with an aim to investigating whether passive accessory motion abnormalities exist with this injury. The second sub-study examined the location of sensations experienced by hamstring injured athletes during the slump test; intent on determining whether the location of symptoms experienced during the test corresponded to those experienced by the participants since time of injury.
1.2.1 Aim of Research

The overall aim of the three central studies of this thesis was to provide greater insight into the slump test in terms of the effect this test has on the local muscular and neural structures in the posterior thigh, in athletes with current hamstring injury. Additionally it was sought to examine whether this test can predict those athletes at risk of hamstring injury. It is anticipated that the evidence provided from this research project will expand the current knowledge available relating to the slump test, thereby encouraging evidence based practice amongst clinicians; particularly those who work with athletes.
1.2.2 Objectives of Research

*Study 1:* To investigate the slump test as a predictive tool for hamstring injury occurrence.

*Study 2:* To examine muscle, pain and resistance onsets during the slump test in athletes with a clinically diagnosed hamstring strain.

*Study 3:* To determine the effect hamstring injury has on longitudinal excursion of the sciatic nerve during the slump test.

*Study 4:* To examine if abnormal vertebral motion of the lumbar spine is present in athletes with current hamstring injury.

*Study 5:* To present the location of symptoms experienced during the slump test in hamstring injured athletes.
Chapter 2

The slump test in undergraduate education and postgraduate clinical practice.

2.1 Introduction

Whilst undertaking this research project, it became apparent that no information exists on the use of the slump test in clinical settings by graduate physiotherapists and sports rehabilitators. Despite being advocated as a treatment and diagnostic tool for patients of lumbar spine and lower limb pathologies (Butler, 1991, Shacklock, 2005a), it is unknown whether the slump test is actually used in clinical practice in the U.K. Not only is the postgraduate use of the slump test unknown, but there is no information as to whether clinicians are introduced to the concept of neurodynamics at undergraduate level, and if so, the extent of the focus on this concept.

To gain an insight into the application of the slump test in physiotherapy and sports rehabilitation working environments in the U.K., a questionnaire was constructed to gain basic information from practising clinicians regarding their use of this test. Undergraduate institutes within the U.K. were contacted to determine the integration of the slump test and neurodynamics into their
respective course curriculum. Ethical approval for the distribution of all questionnaires was obtained from the University of Salford's ethics committee.

2.2 Aim

The aim of this study is to investigate the use of the slump test as a diagnostic and treatment tool amongst graduate therapists, including establishing clinicians’ interpretation of what factors constitute a positive slump test. Additionally, the implementation of the slump test and neurodynamics into undergraduate third-level education is also investigated.

2.3 Method

A comprehensive search of Universities and Colleges Admissions Services (UCAS; www.ucas.ac.uk) revealed 30 institutes within the U.K. who conduct full-time undergraduate physiotherapy degree level programmes, whilst six establishments cited Sports Rehabilitation as a full-time course. One member of each teaching team at each institute (n=36) was contacted in writing, via e-mail, requesting answers to the questions overleaf.
Question 1: Is neurodynamics taught at undergraduate level on your full time undergraduate physiotherapy or sports rehabilitation programme in the institute?

Question 2: Do you teach neurodynamics as a module in isolation, or as part of a module?

Question 3: Do you teach the slump test, as part of the neurodynamics concept?

As the aim of this particular part of this thesis was to simply obtain an essence as to whether the slump test is taught at undergraduate level, it was deemed the questions were sufficiently in-depth. It was not the intention of this study to delve into the exact teachings of the slump test at undergraduate level but merely to gain an understanding as to whether neurodynamics, in specific the slump test, is actually taught, in some form, in third level education on sports rehabilitation and physiotherapy full-time undergraduate programmes.

To investigate the use of the slump test in clinical practice by qualified, practising therapists, a total of 128 questionnaires (Appendix A) were issued to sports rehabilitators and physiotherapists at the annual British Association of Sport Rehabilitators and Trainers (BASRaT) conference and to the English Institute of Sport (EIS) in the North West of England between November 2009 and February 2010. The aim of this questionnaire was to gauge the use of the
slump test as both a diagnostic and treatment tool at postgraduate level, in addition to establishing what constitutes a positive slump test amongst therapists.

2.4 Results

Nineteen (19, 53%) of the 36 institutes approached, who conduct full-time, undergraduate sports rehabilitation or physiotherapy courses, responded to the questions issued. All (100%) of the institutes integrated neurodynamics into their undergraduate physiotherapy or sports rehabilitation programmes. The concept of neurodynamics was taught as part of a module as opposed to in isolation at all institutes. All (100%) of the participating institutes, who replied to the questions, reported the slump test to be taught as part of the neurodynamics concept.

The questionnaire issued to postgraduate clinicians had an overall poor response rate as only 27 (21% of questionnaires issued) responses were obtained. Sixteen sport rehabilitators and eleven physiotherapists, all currently practising, responded to the questionnaire. Of the 27 responses obtained, 26 clinicians used the slump test as a diagnostic tool in the physical assessment of a patient. As a diagnostic tool, the slump test was used by the majority of clinicians in patients presenting with lumbar pain (96%), hamstring strains (88%), posterior thigh pain (77%) and gluteal pain (77%) (Figure 2.1). Other conditions where clinicians typically use the slump test during the physical examination were calf
pain (73%), hip pain (54%) and lower lateral leg pain (54%). Figure 2.1 illustrates the top ten conditions which the slump test is used as a diagnostic and treatment tool, amongst graduate physiotherapists and sports rehabilitators in the U.K.

![Graph showing percentage of clinicians using the slump test as a diagnostic tool compared to a treatment tool for various conditions.](image)

**Figure 2.1:** Percentage of clinicians who use the slump test as a diagnostic assessment tool (n=26) and treatment tool (n=17) in patients presenting with pain of differing anatomical locations.
Nearly two-thirds (n=17; 63%) of therapists reported using the slump test as a treatment tool, whilst the remaining clinicians (n=10) did not. Of those therapists who use the slump test as a treatment option, the majority use it in patients with lumbar pain (82%), hamstring strains (82%), gluteal pain (82%) and calf pain (76%) (Figure 2.1).

Of the 27 therapists who participated in this study, 78% of those regarded a positive slump test to occur when a patient’s symptoms are reproduced during the test (Figure 2.2). 63% of the cohort regarded structural differentiation decreasing patient symptoms as a positive slump test, whilst just under half the population (48%) accepted structural differentiation supporting a neurogenic source as an indicator for a positive test. Asymmetry between limbs, in terms of symptoms or joint range of motion was disregarded by over 60% of therapists as representing a positive slump test.
Factors which constitute a positive slump test

Figure 2.2: The percentage of clinicians’ interpretation of what constitutes a positive slump test.
2.5 Discussion

Whilst clinicians appear to use the slump test as a diagnostic tool to a relatively large extent, there is not the same inclination to use this test as a treatment tool (Figure 2.1) with 33% more therapists using the slump test for diagnostic rather than treatment purposes. It is possible that there is a lack of understanding amongst clinicians as to how to use neurodynamic tests as a treatment tool, and for what specific conditions. The teachings of the slump test was discovered to represent only a segment of a module in the undergraduate physiotherapy and sports rehabilitation courses who participated in the study (section 2.4; page 95), therein lies the possibility that neurodynamics, and in specific the slump test, is not covered in sufficient detail or depth within the curriculum. No institute had an entire module dedicated to neurodynamics and this limited time in teaching such a vast concept, may lead to a lack of understanding at not only undergraduate level, but continuing into postgraduate practice. It is interesting that despite the lack of up-to-date research, particularly in-vivo, of the slump test, that it is widely integrated into third-level education within the U.K. Forming part of the curriculum at higher level education in health professional courses such as physiotherapy and sports rehabilitation supports the continued research which is being undertaken in neurodynamics.
The trend of graduate therapists using the slump test as a diagnostic and treatment tool in suspected conditions which correspond to the distribution of the sciatic nerve is apparent from Figure 2.1, as the majority of therapists support the use of this test in patients with lumbar pain, hamstring strain, posterior thigh pain, calf pain and lower leg pain. Despite this however, almost one in five clinicians (19%, n=5) utilised the slump test when diagnosing patients with anterior thigh pain, whilst 33% used the test diagnostically in patients with groin pain. The femoral nerve test is regarded by Shacklock (2005a) as a more suitable means of evaluating neural mechanosensitivity in patients with thigh, groin and knee pain as opposed to the slump test. However, cadaveric research has shown trunk and neck flexion to cause movement of the upper lumbar nerves (L1 and L2) (Inman and Saunders, 1942; Brieg and Marions, 1963), suggesting therefore that the slump test would most likely cause movement of these nerve roots and thereby assess mechanosensitivity. Consequently, the anterior thigh, groin and anterior lower limb are all areas in which positive responses may be elicited during the slump test. The multiple connections of the lumbar and lumbosacral plexus can therefore make the slump test quite a difficult neurodynamic test to interpret.

It appears that physiotherapists and sports rehabilitators rely on symptoms indicative of neural pathology or symptom reproduction as an indicator for a positive slump test. This however, excludes those patients which may have covert responses during the slump test. Two abnormal primary responses to neurodynamic tests exist according to Shacklock (2005a); overt and covert...
responses. An overt response is one whereby the patient's symptoms are reproduced during the neurodynamic test and the differentiation of those symptoms is positive (Shacklock, 2005a). Alternatively however, a covert response is one whereby symptom reproduction does not occur in response to the test, yet an abnormality, be that in the form of asymmetry of symptoms or a loss of range of motion (Shacklock, 2005a) nonetheless exists. It appears from the results of this sub-study that clinicians primarily focus on overt responses, with only a third of the cohort considering patients with decreased range of motion at the knee as a positive slump test.

Both covert and overt responses to the slump test are examined in this thesis; the former being measured in the subsequent chapter whereby the effect structural differentiation has on knee angle in healthy individuals is examined. Additionally, the difference between limbs is also investigated as a predicative factor for hamstring injury. Following this, knee angle during the slump test is yet again measured in athletes with a current clinically diagnosed hamstring strain. However, in this same population, overt responses, in terms of the location of are also measured.

It is evident that despite its widespread integration into undergraduate physiotherapy and sports rehabilitation programmes in the U.K., the use and interpretation of the slump test amongst practising clinicians is variable. It is
unknown if this occurs as a consequence of the time allocated at undergraduate level to educate students in the concept of neurodynamics and the slump test whereby perhaps an insufficient depth of theory is covered in the curriculum. Perhaps it is the complexity of the slump test itself, whereby sensations can be experienced in all regions of the lower extremities during this test which lead to varying interpretations of the outcomes measured.

The importance of progressing and developing the current research into neurodynamics, in specific, the slump test, is vital to support and encourage its use by student and graduate health care professionals. The paucity of up-to-date in-vivo research into the slump test can potentially cause a lack of evidence based practice amongst clinicians for this test. It is vital that research continually evolves and develops in the area of neurodynamics and the slump test, as this clinical topic is still in its developmental stage in both research and clinical worlds. Whilst cadaveric research by numerous authors (Inman and Saunders, 1942, Falconer et al., 1947, Smith, 1956; Breig and Marions, 1963, Goddard and Reid, 1965) demonstrates the effect lower limb and trunk movement has on the spinal and peripheral nerves, in-vivo examinations of the sciatic nerve during the slump test is lacking. Following Ellis et al's (2008) study highlighting good reliability of using ultrasound in examining the sciatic nerve in the posterior mid-thigh during a sliding technique of the slump test, this is a potential starting point from which further in-vivo research can commence.
The questionnaire issued in this thesis is not without its limitations, particularly the overall poor response rate. Despite being issued at an annual conference of sports rehabilitators, few clinicians actually responded to the questionnaire, potentially creating bias within this study as only those who may actually have an interest or an understanding of the slump test may have responded. Those who abstained from completing the questionnaire may not actually use or value the slump test and therefore may have disregarded the questionnaire itself; this population is therefore not represented in the findings of this study.

Due to the distribution of the questionnaire at a conference for therapists who predominantly work in sport and amongst the physiotherapists at the English Institute of Sport, all of whom work with athletes; these findings cannot be extrapolated to therapists who practice outside of these remits. Therefore the findings of the questionnaire are limited in its applicability to therapists in general.

A more effective recruitment strategy would involve distributing the questionnaire via the physiotherapy professional body (The Chartered Society of Physiotherapists) to encompass the views of non-sporting therapists who may use the slump test clinically. Additionally, using an on-line questionnaire which clinicians could access at any time without the inconvenience of completing a paper version may have generated a larger response rate. Telephone interviews are another recruitment method which may have been utilised.
The questionnaire, following initial development, was issued to five practising clinicians, both sports rehabilitators and physiotherapists for pilot testing, in which to gain feedback prior to its distribution to a wider audience. General comments following the pilot study was to ensure a vast array of conditions to assess the diagnosis and treatment uses of the slump test, including pathologies regarded by Shacklock (2005a) as not substantially assessed using the slump test (e.g. anterior thigh pain). Initially only patient complaints of symptoms in the distribution of the sciatic nerve and myotomal and dermatomal abnormalities were included, but these were expanded to include the anterior thigh, groin, adductor and upper limb. The pilot study also enabled the author to determine the ease and speed at which the questions could be completed.

2.6 Summary

Over-all, the questionnaire utilised in this thesis provided an insight into the use of the slump test as a diagnostic and treatment tool at postgraduate level in the U.K., albeit in those clinicians working predominantly in sport, with therapists having a tendency to use this tests for diagnostic purposes as opposed to treatment. Future research into the use of this neurodynamic test should incorporate a population beyond that of sport with an aim to encouraging those who disregard the slump test as a useful clinical tool to complete the questionnaire also.
Chapter 3
Study 1

Can the slump test be used as a predictive tool for hamstring injury?

3.1 Introduction

Possessing the ability to identify athletes susceptible to hamstring injury would innately decrease the incidence rate of injury and re-injury to this muscle group. Numerous variables such as decreased hamstring strength (Cameron et al., 2003), being of aboriginal descent (Verrall et al., 2001), having a history of posterior thigh injury (Arnason et al., 2004, Gabbe et al., 2005, Hagglund et al., 2006) and advancing age (Bennell et al., 1998, Orchard, 2001, Verrall et al., 2001) are proposed predictive factors for hamstring injury occurrence. It is apparent from the aforementioned proposed risk factors, that hamstring injury occurrence arises predominantly from intrinsic factors, as opposed to external factors, such as environmental conditions or playing surface.

The key to reducing the occurrence of hamstring injury is to identify and address the risk factors which are reversible for this injury (Gabbe et al., 2006).
Both Askling et al. (2003) and Croisier et al. (2002) have reported reductions in the incidence of hamstring injury following the implementation of strength training programmes specific to this muscle group. Similarly, Verrall et al. (2005) reported a significant reduction in hamstring injuries in AFL players following the implementation of a sport specific intervention programme which included an exercise mimicking the body position an athlete adopts prior to hamstring injury occurrence.

Verrall et al’s (2005) unpublished observations are that immediately prior to hamstring injury onset when an athlete is reaching to catch a ball whilst sprinting or accelerating, the trunk of the athlete is in a flexed position as the knee concomitantly extends to allow for heel strike; a theory portrayed in previous research (Heiderscheit et al., 2005; Schache et al., 2009; 2010). Schache et al. (2009; 2010) hypothesised that the hamstrings are most susceptible to injury during the terminal swing phase of sprinting as most of the inertial force acting about the knee joint is imparted onto the hamstrings as they strive to decelerate the swinging shank. Schache et al. (2009) also discovered 3.3° more flexion on the side of the trunk corresponding to the injured limb immediately prior to hamstring injury onset at the point of heel strike in an athlete who was running. A sustained position of trunk flexion was also reported by Heiderscheit et al. (2005) in an athlete immediately prior to hamstring injury occurrence during incline running on a treadmill. Whilst very much an unvalidated observation made by Verrall et al. (2005), there lies potential that the position of
the trunk, as the knee prepared for foot strike, may be a contributing factor to hamstring injury occurrence.

Whilst simultaneous trunk flexion and knee extension during running may not only affect the hamstring muscles, there is the possibility that alternative anatomical structures which connect the trunk and lower limb, such as nerve, may also be vulnerable to injury. The ability of the nervous system to withstand and adapt to the mechanical stresses placed on it, is essential to prevent injury (Shacklock, 1995). Stresses applied to a tissue, even of low magnitude, can cause injury to that tissue (Mueller and Maluf, 2002).

Low magnitude stress applied for long duration or repetitively to a nerve will ultimately cause pathological changes within that structure (Mueller and Maluf, 2002) affecting its vascular, connective tissue and conduction properties (Nee and Butler, 2006). Repetitive tensile, friction or compressive forces acting in the proximity of a nerve can cause mechanical irritation of the nerve (Butler, 1991) leading to decreases in intraneural circulation and axoplasmic flow which then causes an increase in intraneural pressure of the nerve (Nee and Butler, 2006). Intraneural pressure of 30mmHg has been reported to cause intraneurial and extraneurial oedema in nerves (Rempel and Diao, 2004). Interestingly however, Borrelli et al. (2000) discovered intraneural pressure of 55mmHg in the sciatic nerve in cadavers during the SLR. If this neurodynamic test can cause an increase in local intraneural pressure of the sciatic nerve beyond a level which
has previously been reported to cause increases in neural oedema (Rempel and Diao, 2000), it is possible that in an athlete who executes a modified slump test whilst sprinting and reaching to catch a ball (i.e. trunk flexion and knee extension), that repetitive subtle increases in intraneural pressure occurs, with possible resultant inflammation of the neural tissues. Once neural connective tissues are inflamed, the nervi nervorum, located in this connective tissue, become sensitive to mechanical stimuli such as movement (Nee and Butler, 2006) and may therefore lead to neural mechanosensitivity (Butler, 2000). Whether the repetitive motion of simultaneous trunk flexion and knee extension which occurs in sports such as rugby and AFL actually causes increased intraneural pressure and subsequent inflammation of the neural connective tissue is unknown. However, to date, only one study (Gabbe et al., 2005) has evaluated whether neural mechanosensitivity is present prior to hamstring injury occurrence.

Gabbe et al. (2005) investigated whether the slump test can predict risk of hamstring injury, whereby an active version of the test was conducted on a cohort of 126 community level AFL players. Whilst the authors reported the slump test as incapable of identifying athletes at risk of hamstring injury, the test was conducted actively by the participants themselves. Despite being a replica of the slump test method advocated by Shacklock (2005a), the authors did not apply overpressure to the thoracic and cervical spines. It is recommended that overpressure during cervical flexion be applied as part of the standard slump test,
and only omitted in patients whose condition appears highly irritable, sensitive or
the test is contraindicated (Shacklock, 2005a). As the aim of the slump test is to
increase the distance between the end points of the nervous system (Shacklock,
2005a), this effect could be decreased in a patient whereby over-pressure is not
applied.

No research to date has evaluated the effect of over-pressure applied to
the cervical spine during the slump test its effect on symptom production or knee
angle. When viewing Dilley et al's (2003) research, placing the shoulder joint at
90° abduction as opposed to 45° abduction as the wrist moved from neutral to
extension, caused a 0.5% increase in strain of the median nerve. Altering the
position of one joint involved in a neurodynamic test influenced the magnitude of
strain of the nerve being assessed in Dilley et al's (2003) study. It is possible that
over-pressure on the thoracic and cervical spines during the slump test, coupled
with a clinician passively moving the knee into extension as maximal ankle dorsi-
flexion is maintained, would collectively cause greater strain on the sciatic nerve.
Consequently, the mechanosensitivity of the nervous system may not be
effectively assessed in an active slump test. Considering Gabbe et al. (2005)
utilised healthy AFL players, it is unclear why a passive slump test with cervical
overpressure was not conducted in the study, the reasoning behind not being
disclosed by the authors.
If a predictive risk factor such as strength can identify athletes at risk of hamstring injury, and when addressed can actually decrease the occurrence or recurrence of this injury (Croisier et al., 2002, Verrall et al., 2003) there is no reason why the sensitivity of the neural system to mechanical stresses cannot be a proposed risk factor also. There lies the possibility that nerve sensitisation to mechanical stresses may be a predecessor to hamstring injury occurrence; however, whether the slump test is sensitive enough to predict hamstring injury occurrence as a consequence of abnormal mechanosensitivity is unknown.

3.2 Aim

The aim of this study was to examine whether the slump test, conducted pre-season, can predict athletes at risk of hamstring injury.

This study investigates the passive slump test as a predictive tool for hamstring injury in professional and semi-professional football and rugby union players in the U.K. Age and a history of hamstring injury are also examined as predictive factors for hamstring injury based on previous literature (Arnason et al., 2004, Bennell et al., 1998, Gabbe et al., 2005, Hagglund et al., 2006, Orchard, 2001, Verrall et al., 2001). The effect of cervical flexion on knee angle during the slump test is also evaluated in all individuals and between those who sustain a hamstring injury during the follow-up period and those who do not.
3.3 Method

3.3.1 Participants

Convenience sampling was used for this study whereby letters of approach were issued to the senior club physiotherapist or sports rehabilitator at professional and semi-professional football, rugby union and rugby league clubs around the UK detailing the background and testing procedures of the study. Of 25 clubs approached, five of those agreed to participate in this study. Following this, participant information sheets were issued to each club (Appendix C), whereby the players at the respective club could ascertain whether they wished to participate in the study.

A total of 92 professional and semi-professional football (n= 55) and rugby union (n= 37) male players (range 17-39 years; mean age 25±5 years) from five different clubs\(^1\), were prospectively examined during the 2007-2008 pre-season (June 2007 to August 2007 inclusive), by the same examiner, using the passive slump test. A professional athlete was one whose full-time occupation was their respective sport, whilst a semi-professional athlete participated part-time in their chosen sport, receiving payment for doing so. Players who were currently participating in full training and training matches were included in this study. Subjects deemed unfit to participate in competition or training by the club physiotherapists were excluded. All testing procedures were undertaken at each

\(^1\) Accrington Stanley Football Club, Bury Football Club, Doncaster Rugby Union Football Club, Kilmarnock Football Club, Sedgley Park Rugby Union Football Club.
participant's respective club. All subjects gave informed written consent (Appendix C) prior to commencing the study, which had received prior approval from the University of Salford ethics committee (Appendix B).

3.3.2 Testing Protocol

3.3.2.1 The Slump Test

All subjects had markings placed on both legs at the following anatomical locations prior to testing: greater trochanter of the hip, lateral epicondyle of the knee and the lateral malleolus of the ankle. Testing was conducted before all training sessions, where no warm-up or stretching preceded testing. The participant sat on a table with thighs fully supported, knees together and popliteal fossa against the edge of the table with the knees in a resting, flexed position. Holding the sacrum in a vertical position, the subject “sagged” or slumped the trunk towards the hips, maintaining the cervical spine in a neutral position. A strap was then placed across the shoulders below C7 vertebra, to ensure constant overpressure of thoraco-lumbar flexion. The cervical spine was then moved, into either flexion or extension. The subject was requested to look at the ceiling for cervical extension and to bring the chin to chest for cervical flexion, the latter of which the examiner applied overpressure (Figure 3.1). In this position, the examiner then applied maximum dorsi-flexion to one ankle before extending the ipsilateral knee to the onset of resistance, as determined subjectively by the examiner. Onset of resistance (R1) was defined as the point where the examiner
“feels” resistance to the movement (Shacklock, 2005a). The order of the cervical spine position during the slump test, and the initial limb to be examined was randomised for all participants.

Figure 3.1: The passive slump test and cervical flexion.

Two cameras (Nikon Coolpix 990 3 mega pixels) were set up in the sagittal plane to both sides of the subject and the camera closest to the tested limb was used to photograph the knee position at the point of onset of resistance as indicated by the examiner, for both cervical spine positions during the slump test. The cameras were orientated equidistant from the centre of the table with which the athletes were seated during the slump test.
Three trials were conducted for both cervical flexion and extension on each limb and the testing order was randomised. Each subject had a brief rest between each trial. Full knee extension was taken as 180 degrees. Subjects were continuously monitored for the presence of adverse symptoms during the testing procedures, whereby withdrawal would have been implemented should altered sensations or pain occur during testing. All subjects however, completed all testing components with no withdrawal requests. Following data collection, all knee angles during the slump test were measured, in degrees, using Image J (2006; National Institutes of Health, U.S.A).

3.3.3 Follow-up Procedure

Following termination of the season (April 2008), each club physiotherapist was contacted in writing and asked to provide information regarding all the players who had been previously tested (Appendix D), as to whether they had sustained a hamstring injury over the season. The physiotherapists were then requested to provide information on those who had sustained a hamstring injury such as the limb which had been injured, date and mechanism of injury, time absent from competition and if the injury reoccurred. All the participating clubs responded to the follow-up request.

The diagnosis of each hamstring injury was entirely dependent upon the diagnostic capabilities of the medical staff (physiotherapist/sports rehabilitator and club doctor) at the participating clubs where the diagnosis was initially made,
with no participant undergoing radiological investigation to verify the injury. Whilst this may be considered a problematic factor, particularly considering almost 20% of athletes with apparent hamstring strains have no evidence of muscular pathology on MRI (Verrall et al., 2001), none of the clubs actively referred any injured athlete for further intrinsic investigations. Perhaps this is a true reflection of the use of MRI or ultrasound scans for hamstring injury diagnosis within professional and semi-professional sport in the U.K.

No guidelines were provided as to what typically constitutes a hamstring strain as it was assumed that clinicians working at semi-professional and professional sporting level would have superior skills in this area, being exposed to these types of injuries on a relatively regular basis. However, to evaluate the standardisation of the therapists for diagnosing a hamstring strain, three key clinical elements associated with hamstring injury were included on the feedback table (Appendix D). These were; decreased isometric strength with or without pain as measured using a manual isometric contraction by the clinician, decreased range of motion via passive straight leg raise test (hip flexion with knee extension) and finally, pain on palpation of the suspected site of injury (Heiderscheit et al., 2005). All the participating physiotherapists reported each of these basic findings for posterior thigh injury to occur in all participants.
3.3.4 Data Analysis

The mean of the three trials for cervical flexion and extension in both limbs was calculated. Independent t-tests were used to compare the knee angle achieved during cervical flexion and extension during the slump test, between players who sustained a hamstring injury post-testing and their uninjured counterparts. Dependant t-tests were utilised to compare the knee angle obtained at onset of resistance during the slump test, for both limbs during cervical flexion and extension, within the uninjured and injured groups individually. The value of significance was p<0.05.

In this particular study, to determine the ability of the slump test in predicting hamstring injury, a multivariate analysis with stepwise logistic regression was undertaken, as two more variables were added into the equation. The differences in knee angle between cervical flexion and extension positions during the slump test, participant age and history of hamstring injury were the variables entered into the stepwise logistic regression. Statistical analysis was conducted using Statistical Packages for Social Sciences (SPSS, version 15).
Finally, delta scores were calculated to determine the difference in knee angle between both limbs as a consequence of cervical flexion in both groups (see below).

Delta score for uninjured group = (Knee angle cervical extension - knee angle cervical flexion)right leg - (Knee angle cervical extension - knee angle cervical flexion)left leg

Delta score for injured group = (Knee angle cervical extension - knee angle cervical flexion)uninjured leg - (Knee angle cervical extension - knee angle cervical flexion)injured leg

3.5 Results

A total of 9 players (9.78%) of the entire cohort reported hamstring injury in the season subsequent to initial testing, with one-third of those (33.3%) suffering from recurrence of the injury in the same season. Of the injured cohort, six players (66%) reported having a history of hamstring injury prior to the occurrence of the injury in this study, with three players citing the injury occurring to the same leg. Of those who reported a recurrent injury to the same leg, the
mean time since initial injury to recent injury was 22 weeks (range 2-56 weeks). The mean age of the injured group was 26.7±3.4 years (range 20-30 years) and the average time absent from competition was 26.8±11.3 days (range 11-42 days).

No significant difference was found in knee extension angle between the right and left limb during the cervical flexion (p=0.56) and extension (p=0.37) components of the slump test in the group of players who sustained no hamstring injury (n=83). Consequently, for the purpose of further analysis, data was pooled for the knee angle for both limbs during both components of the slump test for this group. The mean knee angle (with Standard error of mean (SEM)) achieved during the slump test for cervical flexion and extension in this group was 162.2±1.03° and 168.5±0.79° respectively. Utilised as a structural differentiating manoeuvre during the slump test, cervical flexion elicited a significant decrease in knee extension angle of 6.3±5.0° (95% Confidence Interval (CI), 5.2°-7.5°) (p=0.001) in the uninjured group.

In those who had sustained a hamstring injury subsequent to testing, the mean knee angle (±SEM) achieved during the cervical flexion component of the slump test was 160.7±1.8° for the injured limb and 157.9±2.9° for the uninjured limb. Cervical extension elicited knee angles of 167.5±1.5° and 167.5±1.9° for the injured and non-injured limbs respectively. No significant difference in knee angle between the injured and uninjured limbs during cervical flexion (p=0.262) and
cervical extension (p=0.996) was observed in this group. Cervical flexion induced a significant decrease in knee extension range of 6.8±5.5° (95% CI 3.2°-10.4°) and 9.6±4.7° (95% CI 6.5°-12.7°) for the injured (p=0.006) and un-injured limbs (p=0.0003) respectively; a non-significant difference (p=0.059) when the limbs were compared.

No significant difference in knee angle between the uninjured group and the injured limb of the hamstring group was found with either cervical flexion (p=0.652) or cervical extension (p=0.683) and when the difference between knee angle during both structural differentiating components was examined (p=0.806). The mean knee angle (with Standard Error of Mean (SEM)) obtained for both structural differentiating components during the slump test for the control group (mean of right and left legs utilised) and both limbs of the injured group is presented in Figure 3.2.
Full knee extension = 180°.

Figure 3.2: Mean knee angle (with Standard Error of Mean) during cervical flexion and extension of the slump test in the injured and uninjured legs of the injured group and the mean of both limbs in the non-injured group.

A difference in knee angle between cervical flexion and extension of 5.9° and 6.8° for the right and left legs respectively was evident in the non-injured group. This difference between limbs (delta score) in the uninjured group was therefore 0.9°. In the injured group the difference in knee angle obtained between the cervical components of the slump test, in the injured and non-injured limbs of
the injured group was 6.8° and 9.6° respectively; with a subsequent delta score of 2.8°. This difference was discovered to be non-significant (p=0.059).

The results of the Stepwise Logistic Regression revealed previous hamstring injury as the only predictive factor to identify susceptibility of professional and semi-professional rugby union and football players to hamstring injury. The structural differentiating component of the slump test (i.e. the difference in knee angle between cervical flexion and extension) and participant age at time of injury were determined to be unable to predict hamstring injury.

Whilst age was not a predictive factor for hamstring injury in this study, a breakdown of the age categories revealed the incidence of this injury to increase with advancing age beyond 20 years of age (Table 3.1)

Table 3.1: The incidence of hamstring injury according to age category (n=8).

<table>
<thead>
<tr>
<th>Age range</th>
<th>Total number of players in each age group</th>
<th>Number of injured players</th>
<th>Injury percentage per age category</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;20</td>
<td>11</td>
<td>1</td>
<td>9%</td>
</tr>
<tr>
<td>20-24</td>
<td>35</td>
<td>1</td>
<td>2.85%</td>
</tr>
<tr>
<td>25-29</td>
<td>27</td>
<td>4</td>
<td>14.8%</td>
</tr>
<tr>
<td>30-34</td>
<td>13</td>
<td>2</td>
<td>15.0%</td>
</tr>
<tr>
<td>35-39</td>
<td>6</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

* Note: one hamstring injured athlete did not disclose age.
Players aged between 25-29 years in this study had the highest level of hamstring injury occurrence (Table 3.1), accounting for almost 50% of all the hamstring injuries. 15% of all players who participated in this study, aged between 30 and 34 years, sustained a hamstring injury. The oldest players in this study (35-39 years) cited no hamstring injury occurrence; however this age category has the least number of players (n=6).
3.6 Discussion

The aim of this study was to investigate whether the neurodynamic test, the slump test, can be used as a predictive tool for hamstring injury in athletes. The slump test and age were discovered to be unable to predict hamstring injury occurrence, whilst a history of hamstring injury was a predictive factor. Cervical flexion, as a structural differentiation manoeuvre during the slump test, caused a significant decrease in knee extension all athletes in this study, irrespective of injury status. No significant difference in delta score between the injured and non-injured groups were evident.

The effect structural differentiation (i.e. cervical flexion) had on knee angle obtained during the slump test in this study (range 6.3° to 9.6°) reflect that of previous work (range 5.4° to 8.9°) (Fidel et al., 1996, Herrington et al., 2008, Johnson and Chiarello, 1997). Differences in the effect cervical flexion has on the injured and uninjured limbs was visible via the delta score in the group who sustained a hamstring injury at follow-up, with a delta score of 2.8°. The delta score for the uninjured group however was less than 1° (0.9°). It therefore appears that the limb which sustained the hamstring injury during the follow-up period is more mobile (160.7°) during the cervical flexion component of the slump test than the uninjured limb (157.9°) of the injured group; a finding not evident for the cervical extension position of the slump test. It is possible that enhanced or excess neural mobility is a contributing factor to hamstring injury occurrence, as
cervical flexion had a greater impact on the uninjured limb than its injured counterpart, the former achieving less knee extension during cervical flexion.

Greater flexibility during both the sit and reach test and active slump test has been reported in athletes with a history of hamstring injury (Gabbe et al., 2006). Section 2.4 (page 95) of this thesis highlighted how therapists are inclined to use the slump test as a treatment strategy in hamstring injured patients. It is possible that neural mobilisation exercises during rehabilitation cause excess mobility of the sciatic nerve, potentially contributing to the occurrence of injury in this study. Considering four of the six injured athletes in this study who cited a history of previous posterior thigh injury actually sustained the initial injury within 12 months of the more recent injury; three of these being to the same limb, it is possible that enhanced neural mobility may have been present. Regardless of these observations however, the delta score was discovered to be a statistically non-significant, potentially due to the limited number of injured athletes. A substantially larger sample population may have enabled the author to examine this discrepancy in achievable range of motion at the knee during the slump test between limbs which was weakly evident in this study and further investigate Shacklock’s (2005a) viewpoint that asymmetry between limbs during neurodynamic tests is an important measurement to take into account.

The slump test was unable to predict hamstring injury occurrence in rugby union and football players in this study; a finding which concurred with the
research of Gabbe et al. (2005). It is possible that this clinical test, as evaluated using knee range of motion to onset of resistance, is just not sensitive enough to detect minor abnormalities of the nervous system on average three months before the injury occurs, as which was the case in this study. Of the nine players injured, the average time of onset of the hamstring injury following the testing session, was three months (range 1-7 months). Subtle alterations in a nerve’s ability to withstand mechanical strain may be undetectable to a clinical test as gross as the slump test, particularly 12 weeks in advance of the injury actually occurring. Using knee angle as the outcome measurement in the slump test may be too insensitive a measurement despite it being advocated as a useful outcome measurement during neurodynamic tests.

Having a history of injury to the posterior thigh has been deemed a consistent predictor for hamstring strains in literature (Arnason et al., 2004, Bennell et al., 1998, Gabbe et al., 2005, Hagglund et al., 2006, Orchard, 2001, Verrall et al., 2001). Considering a larger portion of the injured group in this study had a history of posterior thigh injury (PTI) (66%; 6/9 players) compared to the non-injured group (25/83; 30%), it is unsurprising that previous hamstring injury should emerge as a predictive risk factor for hamstring strain in this study. It is possible that an incomplete recovery from the initial injury occurred in the injured group as the mean time those athletes took to return to competition was 6.5 weeks (range 2-16 weeks). Of those players with a history of hamstring injury who then sustained another one to the same leg (n=3) in this study, all of these
athletes returned to competition within one month from the initial occurrence. These findings indicate that the time spent recovering and rehabilitating from an initial hamstring injury may be vital in preventing recurrent hamstring injury.

Age is regarded as one of the primary predictive factors for hamstring injury occurrence (Arnason et al., 2004, Gabbe et al., 2005, Hagglund et al., 2006, Orchard, 2001, Verrall et al., 2001). In this particular study, despite age not being a predictive factor for hamstring injury, the incidence of injury increasing with advancing age is visible (Table 3.1). Only one player in the under 20 years age category sustained a hamstring, following which the incidence of hamstring injury increased in every age group, up to the penultimate age group. Those athletes aged between 35-39 years are clearly in the minority compared to the other age categories, most likely due to older athletes being a rarity in full-time professional sports clubs, such as those which partook in this study. Of the 92 athletes who partook in this study, only 19 (20%) were semi-professional athletes; a level in sport where older players may typically enter into following a professional career. Similarly, the <20 years age group in this study is a relatively small sample size, possibly due to athletes of this age not being permanent members of the first team, playing with the academy or developmental squads. Perhaps with an even distribution of athletes into all age categories, a clearer relationship may be evident between advancing age and hamstring injury occurrence. It would also be interesting to expand the current research to incorporate athletic disciplines which do not typically involve the primary
mechanism of injury for hamstring strains (i.e. sprinting and running) (Gabbe et al., 2006, Gabbe et al., 2005) but also activities such as dancing, where hamstring injury reportedly occurs during slow, stretching movements (Askling et al., 2002).

3.7 Limitations

Despite recruiting a sample size and subsequently citing an injury rate similar to that of Bennell et al. (1998), little statistically significant results were unearthed in this study, potentially due to the sample size. Other prospective studies recruited sample sizes ranging from 114 to 222 athletes (Gabbe et al., 2005; 2006; Verrall et al., 2001); all of whom had a higher rate of hamstring injury occurrence than this study ranging from 16%-28%. Due to hamstring injury occurrence being more prevalent in elite sports (Verrall et al., 2001), a decision was undertaken at the initial stages of this research to focus on professional and semi-professional sports to maximise the likelihood of hamstring injury occurrence; a decision, which upon reflection, restricted the sample size of this study.

In retrospect, if academy athletes had been recruited at each participating club, the sample size for the under 20 age group may have increased, as would that of the over thirties if more semi-professional or amateur clubs had been recruited. The trend of hamstring injury occurrence increasing with age may have
been more apparent with a more diverse sample population. A larger scale study incorporating a wide range of ages, from different competitive levels would be ideal for the future to determine whether advancing age, particularly those beyond 30 years of age, is correlated with hamstring injury occurrence.

Whilst Shacklock (2005a) reports asymmetry between limbs during neurodynamic tests to be an important outcome measure to assess, this study cannot rigidly support that viewpoint as no significant difference in delta score was discovered. Whilst the injured limb of those athletes who sustained a hamstring injury at follow-up appears to be more mobile than its uninjured counterpart, as larger range of motion could be achieved at the knee during the cervical flexion component of the slump test, these differences were minimal. A larger sample size may present a clearer picture of the slump test delta score in athletes prior to hamstring injury occurrence, thereby potentially minimising the occurrence of Type II error, which may have occurred in this study. With a small group of athletes having sustained a hamstring injury during the follow-up period, a Type II error may have occurred as differences in delta score may be evident in this population, but undetectable in such a small sample size. Power calculations prior to undertaking this study would have ensured the appropriate sample size was recruited to maximise the possibility of detecting neural abnormalities in athletes prior to hamstring injury occurrence.
3.8 Summary

The passive slump test was unable to predict hamstring injury occurrence in professional and semi-professional football and rugby union players in this study and may therefore be a relatively insensitive tool in identifying the susceptibility of athletes to hamstring injury. Viewing the differences in gross knee angle between cervical flexion and extension obtained at the point of resistance during the slump test did not yield any significant findings; however, it was only when delving deeper into the results, that a potentially interesting finding was discovered; the delta score. Differences in the effect cervical flexion had on knee range of motion between limbs in the injured group was slightly more pronounced than in the non-injured group. However, a limited sample size potentially limited the possibility of a significant finding taking place as the target population was very specific (professional or semi-professional athletes) and dependant on the willingness of entire sports clubs to participate.

The slump test may be too gross or insensitive to identify athletes susceptible to hamstring injury, particularly when there were participants in this study who did not sustain an injury until seven months post-testing. This study supports the possibility that the slump test may not play a role in the aetiology of hamstring injury, particularly considering the variable responses extracted during the slump test. It is possible that predicting hamstring injury so far in advance of its occurrence is too big an undertaking for the slump test. It was therefore decided to go back to basics in this research thesis and examine the slump test
in greater detail in hamstring injured athletes; specifically what happens to the local neural and muscular systems in the posterior thigh during this test. The subsequent chapter examines muscle activity, pain and resistance onsets during the slump test in hamstring injured athletes. The latter variable was examined due to it being a very subjective measurement, entirely dependent on the examiner’s interpretation of when this resistance occurs (Herrington et al., 2008). It is ultimately unknown what the resistance actually occurs in response to; is it muscle activity? Does the pain experienced during the slump test also occur in response to muscle activity? Consequently, the following chapter examines the muscle, resistance and pain onsets during the slump test in hamstring injured athletes.
Chapter 4

Study 2

Muscle activity, pain and resistance onsets during the slump test in hamstring injured athletes.

4.1 Introduction

Subjective reporting of pain onset (P1), onset of resistance as determined by the examiner (R1) and onset of local muscle activity (M1) are commonly used measurements during neurodynamic tests (Balster and Jull, 1997, Coppieters et al., 2002, Hall et al., 1998, van der Heide et al., 2001); all variables which are affected by structural differentiation (Balster and Jull, 1997; van der Heide et al., 2001; Herrington et al., 2008). Van der Heide et al. (2001) reported onset of trapezius activity to occur earlier in elbow extension range during an upper limb neurodynamic test with structural differentiation when compared to a neutral cervical spine position. Onset of pain was also discovered to occur earlier in range of joint motion with structural differentiation during an upper limb neurodynamic test by van der Heide et al. (2001) whilst Herrington et al. (2008) reported R1, as determined by the examiner, to occur significantly earlier in
range of knee extension during the slump test with cervical flexion than extension.

Pain, resistance and muscle onset do not necessarily occur in isolation during neurodynamic tests (Balster and Jull, 1997, Coppieters et al., 2002, Hall et al., 1998, van der Heide et al., 2001). Van der Heide et al. (2001) reported the onset of trapezius activity (M1) to occur earlier in range of elbow extension during an upper limb neurodynamic test than the onset of pain for both a neutral cervical spine position and the structural differentiating manoeuvre. Alternatively however, Balster and Jull (1997) reported no correlation between EMG activity of the upper trapezius and pain perception levels experienced at the elbow extension and CCLF stages in a brachial plexus neurodynamic test. Onset of resistance (R1) as determined by the examiner, was deemed by Hall et al. (1998) to be of no real value as a diagnostic tool in the evaluation of neural tissue mechanosensitivity based on the finding that R1 had no significant bearing on the onset of muscle activity during the Straight Leg Raise (SLR). Onset of muscle activity is one variable which Hall et al. (1998) held in higher regard than an examiner’s determination of resistance onset as a viable, useful measurement tool in patients with lower limb radiculopathy.

The examination of muscle activity onset during neurodynamic testing in a clinical setting is one which may not be undertaken frequently however, possibly due to difficulty in acquiring EMG equipment and the analysis required to
determine onset. Whilst raw EMG traces can be visually inspected to determine the point in time where the EMG signal first deviates or increases from the baseline (Hall et al., 2009, Lee et al., 2007, Vasseljen et al., 2006), this is a very subjective method for determining onset of muscle activity. Computer algorithms are therefore recommended for determining muscle activity onset in an attempt to reduce observer bias (Allison, 2003b, Bennell et al., 2006a, DiFabio, 1987, Dixon and Howe, 2007, Hodges and Bui, 1996, Skotte et al., 2005).

The underlying principle for the computer-based muscle onset determination method utilised in this particular study involves identifying a point, where it exceeds the baseline activity level by a specific number of standard deviations, for a pre-determined period of time (Hodges and Bui, 1996); a method more commonly known as the standard deviation (SD) method (Lee et al., 2007). The advantage of a threshold based on the statistical deviation from the baseline is that it is normalised to any erratic changes in baseline activity (Hodges and Bui, 1996). Variation exists in literature, as to the recommended threshold criteria for computer based EMG onset determination, with authors using between 1SD and 5SD above mean baseline (Allison, 2003, Bennell et al., 2006, DiFabio, 1987, Hodges and Bui, 1996, Skotte et al., 2005).

Higher or lower threshold values can increase the risk of Type II and Type I errors respectively. The potential for Type I error increases when using 1SD above the baseline mean as the muscle could be identified as being active, when
it is not, as the algorithm may detect an early onset of muscle activity (Hodges and Bui, 1996). Contrastingly, whilst increasing the SD can decrease the number of false onsets, it is often at the expense of a temporal delay in onset and therefore the possibility of Type II error is increased (Hodges and Bui, 1996; Allison, 2003). DiFabio (1987) advocated utilising 3SD above the mean baseline values as Type II errors are not cause for concern due to the high resolution of computer assessments. Consequently, 3SD above the mean baseline value was the threshold of choice in determining muscle onset during the slump test, in this particular study.

No research to date has simultaneously evaluated muscle, pain and resistance onsets during the slump test in healthy or pathological individuals. It is important for clinicians to know what interactions occur between pain, resistance and the local muscles during neurodynamic tests, as these are three variables encouraged for use as the end points when conducting neurodynamic tests (Balster and Jull, 1997, Coppieters et al., 2002, Hall et al., 1998, van der Heide et al., 2001).

4.2 Aim

The aim of this study is to evaluate the onset of muscle activity, pain and resistance during the slump test, in professional and semi-professional rugby union players with clinically diagnosed hamstring strains.
The effect structural differentiation has on the onset of muscle activity, pain and resistance is also of interest, to evaluate whether this manoeuvre actually has an effect on the variables measured during the slump test. If structural differentiation, via moving the cervical spine has no effect on pain, muscle activity or resistance onset, its validity for use during the slump test in patients with posterior thigh pain must be queried. With no research currently available as to the onset of pain, muscle activity and resistance during the slump test, the aim of this study is to evaluate these variables during this test, in professional and semi-professional hamstring injured rugby union players.

Prior to examining these variables during the slump test in an injured cohort, a reliability study was undertaken to determine the reliability of the examiner in determining the onset of resistance (R1) during the slump test. Additionally, to determine whether onset of muscle activity can be reliably examined between sessions using surface electromyography (EMG), the inter-session reliability of detecting M1 during the slump test was also assessed. Onset of pain was deemed not appropriate to assess in healthy individuals as they should be asymptomatic, pain is not a common sensation experienced during neurodynamic testing (Boyd et al., 2009).
4.3 Inter-session reliability of muscle and resistance onsets during the slump test.

4.3.1 Method

4.3.1.1 Participants

The onset of resistance and onset of hamstring muscle activity were investigated during the slump test in an asymptomatic cohort. A total of 6 individuals (3 male; 3 female) of mean age 22.8 years (±1.7 years; range 20-25 years) volunteered for this reliability study via convenience sampling. All subjects had no history of injury to the lumbar, thoracic or cervical spine and were considered to be in good health, with no current injury or history of hamstring injury. Ethical approval was obtained from the University of Salford (Appendix B), following which consent was obtained from all participants (Appendix E).

4.3.1.2 Testing Protocol

A default sampling frequency of 1004Hz was used for surface EMG data acquisition using a portable EMG system (Noraxon MT400). A high and low pass filter between 10 and 500 Hz respectively (Noraxon MT400) was utilised and the signal preamplified (×1000). Simultaneous recordings of the surface electromyography (EMG) activity from the biceps femoris and semitendinosus muscles during the slump test were recorded. The right limb only was recorded
for the purpose of this reliability experiment. To reduce electrode-skin impedance, the skin on the posterior thigh surface was initially shaved before being exfoliated by light abrasion (Nuprep, SLE Ltd) and then cleaned using alcohol swabs.

One pre-gelled, self-adhesive silver-silver chloride dual snap electrode, with a centre to centre distance of 2cm (Noraxon Dual Electrodes), was placed in a line parallel to the respective muscle fibers of the biceps femoris and semitendinosous muscles, in between the nearest innervation zone and musculotendinous junction (Cram and Kasman, 1998). A single ground electrode (Noraxon Single electrode) was placed at an electrical neutral site; the lateral epicondyle of the femur.

The specific electrode placement for the biceps femoris muscle was as follows: the electrodes were placed parallel to the muscle fibers, on the lateral aspect of the thigh, two-thirds the distance from the greater trochanter of the femur and popliteal fossa (Cram and Kasman, 1998). To confirm electrode placement the knee was placed in 90° flexion, and the hip in slight lateral rotation. Manual resistance was then applied to the limb whereby the subject attempted to bring their heel to the buttocks (Cram and Kasman, 1998). For semitendinosus, the electrodes were placed on the medial aspect of the thigh, approximately 3cm in from the lateral border of the thigh and approx half the distance from the gluteal fold to the popliteal fossa. To confirm electrode
placement the knee was placed in 90° flexion, and manual resistance was then applied to the limb, which was held in a midline position (Cram and Kasman, 1998).

The subject sat on a table with thighs fully supported, knees together and the popliteal fossa against the edge of the table. Holding the sacrum in a vertical position, the subject allowed the trunk to sag towards the hips, ensuring the cervical spine was in a neutral position. A strap was then placed across the shoulders below C7 vertebra, to ensure constant overpressure of thoraco-lumbar flexion. The cervical spine was then moved, in randomised test order, into either flexion or extension. The subject was requested to look at the ceiling for cervical extension, and to bring chin to chest for cervical flexion; the latter of which the examiner applied overpressure to. The examiner then applied maximum dorsiflexion to the ankle before extending the knee to the point of terminal knee extension. Terminal knee extension was regarded as the point during the slump test where the limb was extended as far as possible, which the subject was comfortable with (Johnson and Chiarello, 1997).

The outcome variables measured during the slump test for this reliability study were onset of resistance experienced by the examiner (R1) and onset of muscle activity (M1) for biceps femoris (M1_{BF}) and semitendinosus (M1_{ST}) muscles; all measured with respect to the knee angle. The operational definitions utilised for this study for each of the variables were as follows:
Onset of resistance (R1): The point where the examiner “feels” resistance to the movement (Shacklock, 2005a).

Onset of muscle activity (M1): The first point where the EMG signal exceeds a threshold level of 3 standard deviations above the mean baseline (Hodges and Bui, 1996, Julius et al., 2004).

Upon feeling the onset of resistance as the knee was moved passively into extension during the slump test, the examiner activated a trigger, via a footswitch (Figure 4.2; page 150). The trigger was connected to the EMG system and its activation subsequently registered on its own individual channel. The entire slump test was recorded by a video camera (Sony Digital Video Camera Recorder) situated in the sagittal plane, whereby the range of knee extension was later analysed via computer software. Full knee extension was taken as 180° based on research which utilised knee range of motion as an outcome measure (Bender and Kaplan, 1963; Cibulka et al., 1986; Abdel-Salam and Eyres, 1995).

Five trials were conducted for both cervical flexion and extension positions on the right limb only. Whilst the cervical movement was randomised for each subject, the same order of testing was used for each subject in the re-test. A repeat testing sessions was undertaken 48 hours following the initial testing procedure, at the same time of day. Subjects were monitored for the presence of adverse symptoms, such as pain or altered sensations during and following the
testing procedures, whereby withdrawal would be implemented should such symptoms occur. All subjects however, completed all testing with no withdrawal requests during, or between testing sessions.

The raw EMG data was exported as text files and subsequently analysed using a specifically constructed computer algorithm constructed in Testpoint (Appendix F). Determining the onset of activity for biceps femoris and semitendinosus was achieved using a custom-made computer algorithm. Onset of muscle activity is defined for the purpose of this experiment, as the first point where the EMG signal exceeds a threshold level of 3 standard deviations above the mean baseline (Hodges and Bui, 1996, Julius et al., 2004). All muscle onsets were subsequently visually inspected to verify the onset time determined by the computer algorithm (Hodges and Bui, 1996).

Each channel was analysed individually, each following the same method; the raw EMG data was full-wave rectified and filtered using a low pass filter of 100Hz. A segment of EMG trace on the channel was selected for baseline, following which the Testpoint programme computed the onset time for that channel. Following this, the EMG data was then visually inspected by the examiner to verify the onsets identified by the computer algorithm (Bennell et al., 2006, Hodges and Bui, 1996). The onset time of biceps femoris, semitendinosus and resistance was computed and recorded for all subjects.
4.3.2 Data Analysis

Knee angles correlating to the onset of resistance experienced by the examiner were determined by inspection of the recordings by the cameras, using Quintic Biomechanics (version 11). The light emitting trigger identified the point where R1 occurred, allowing the examiner to capture the specific frame when the trigger illuminated, and determine the time difference between the onset of the movement and the onset of R1. Referring back to the onset times for the muscles, the time from movement onset to muscle onsets was then computed. Once these values were obtained, Quintic enabled the corresponding knee angle for each variable to be calculated. Full knee extension was regarded as 180 degrees for this study.

Data were analysed using the statistical software package SPSS (version 16). To determine the intra-reliability of the tester at detecting onset of resistance (R1), Intraclass Correlation Coefficient (ICC_{3,1}), Standard Error of Measurement (SEM) and Smallest Detectable Difference (SDD) were calculated for the knee angle corresponding to this variable. Likewise, the knee angle at the point of onset of muscle activity, as identified by the computer algorithm, was utilised to assess the reliability in detecting M1 between sessions. The knee angle obtained for the third trial of each subject for R1, onset of biceps femoris (M1_{BF}) and semitendinosus (M1_{ST}) for initial test and retest, during both cervical spine positions of the slump test, were analysed using an Intraclass Correlation Coefficient (ICC_{3,1}) to assess both the degree of correspondence and agreement
between the trials which were conducted on different days (Portney and Watkins, 2000).

The reliability coefficients were interpreted using the following criteria as utilised by Coppieters et al. (2002):

"Poor" = ICC < 0.40
"Fair" = 0.40 ≤ ICC < 0.70
"Good" = 0.70 ≤ ICC < 0.90
"Excellent" = ICC ≥ 0.90

The standard error of measurement (SEM) was also calculated, as a function of the pooled group standard deviation and the ICC (SEM = SD (pooled) x SQRT (1-ICC)) (Safrit and Wood, 1989). The Smallest Detectable Difference (SDD) at the 0.05 level was determined using the formula SDD = 1.96 x √2 x SEM) (DeBruin et al., 1998), thereby providing an indication of the smallest significant amount of difference in range of motion for each variable that could be detected in subjects. Additionally, 95% Confidence Intervals (CI) were also calculated to assess measurement variability, using the formula (95% CI = 1.96 x SEM) (Portney and Watkins, 2000).

The cumulative effect of repeating the slump test on knee angle was additionally investigated using a dependant t-test, comparing the knee angle
obtained for all variables ($M_{1BF}$, $M_{1ST}$ and $R_1$) during the second and fifth trial for the slump test with cervical flexion, for the initial testing session only. This was undertaken to determine whether significant changes in knee angle during the slump test occurred with each repetition of the test. The level of significance was set at $p<0.05$.

### 4.3.3 Reliability Results

A high reliability with smaller measurement error is essential to render a clinical test suitable for practice; particularly if its use is to determine the effectiveness of a treatment (Coppieters et al., 2002). Assessment of the reliability at detecting $R_1$, $M_{1BF}$ and $M_{1ST}$ indicates that good to excellent reliability was obtained during the slump test, when the cervical spine was in flexion for all variables (Table 4.1).
Table 4.1: The inter session reliability of detecting onset of resistance and onset of muscle activity of biceps femoris and semitendinosus, with respect to knee angle (degrees), during the slump test for cervical flexion and extension (n=6).

<table>
<thead>
<tr>
<th>Neurodynamic Test</th>
<th>ICC₃,₁</th>
<th>SEM</th>
<th>95% CI</th>
<th>SDD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Onset of resistance (R1)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Slump test + CF</td>
<td>0.81</td>
<td>3.64°</td>
<td>7.14°</td>
<td>10.10°</td>
</tr>
<tr>
<td>Slump test + CE</td>
<td>0.68</td>
<td>4.86°</td>
<td>9.53°</td>
<td>13.48°</td>
</tr>
<tr>
<td>Onset of muscle activity (M1) of Biceps Femoris</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Slump test + CF</td>
<td>0.87</td>
<td>4.34°</td>
<td>8.51°</td>
<td>12.03°</td>
</tr>
<tr>
<td>Slump test + CE</td>
<td>0.75</td>
<td>4.76°</td>
<td>9.33°</td>
<td>13.2°</td>
</tr>
<tr>
<td>Onset of muscle activity (M1) of Semitendinosus</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Slump test + CF</td>
<td>0.95</td>
<td>1.96°</td>
<td>3.84°</td>
<td>5.43°</td>
</tr>
<tr>
<td>Slump test + CE</td>
<td>0.79</td>
<td>4.30°</td>
<td>8.43°</td>
<td>11.93°</td>
</tr>
</tbody>
</table>

"ICC"=Intraclass Correlation Coefficients
"SEM"=Standard error of measurement
"95% CI"= confidence interval
"SDD"= smallest detectable difference
"CF"=cervical flexion
"CE"=cervical extension

Whilst the examiner was considered to have good reliability in detecting the onset of resistance during the slump test with cervical flexion (ICC=0.81), a "fair" reliability score (ICC=0.68) was achieved when the spine was in extension. The reliability between sessions of detecting onset of muscle activity during the slump test for both cervical flexion and extension ranged from good to excellent.
according to the ICC scores (ICC range 0.75-0.95) with SEM scores under 5°. This is an extremely good result considering how temperamental surface EMG can be, as there are many variables which can reduce reliability significantly; a primary one being error in the placement of electrodes between two different testing sessions. In an attempt to standardise this and reduce the chance of error, the examiner upon initial testing of a subject, measured the distance of each electrode from the popliteal crease to the centre of the electrodes; thereby enabling the electrodes to be placed in an almost identical location at retest.

Interestingly, whilst the ICC scores for R1 in the slump test with cervical extension decreased compared to when the cervical spine was flexed, the same was not evident for M1BF and M1ST. The ICC scores for these variables still remained in the “good” category according to Coppieters et al. (2002). Overall, this study highlights that good reliability can be achieved for determining the onset of muscle activity for the biceps femoris and semitendinosus muscles when using surface EMG during the slump test.

An increase in knee range of motion was evident between trials 2 and 5 for all variables (M1BF, M1ST and R1) during the slump test with cervical flexion at initial testing, indicating the knee is capable of further extension with sequential trials of the slump test with cervical flexion (Figure 4.1). During trial 5, biceps femoris muscle onset occurred 3.6° later in range of knee extension of the slump test than that of trial 2, which occurred at 155.1° of knee extension. Similarly,
semitendinosus muscle onset occurred later during the slump test at trial 5 than trial 2 (166.0° and 159.6° respectively). Little difference existed in the knee angle at which onset of resistance occurred between trials during the slump test (trial 2=161.8°; trial 5=162.4°).

Figure 4.1: Knee angle obtained during the initial testing session of the slump test with cervical flexion for Trial 2 and Trial 5 of the initial testing session.

Despite the increases in the onset of muscle activity and resistance which occurred between trials in Figure 4.1, these were found to be statistically non-significant (p>0.05); findings similar to that of Coppieters et al. (2002) who also cited non-significant increases in joint range of motion following successive trials during neurodynamic testing. Nonetheless however, the possibility that successive trials of a neurodynamic test will cause increased range of motion at a joint is possible, as Herrington (2006) reported significant increases in knee
extension following sliding and tensioning mobilisation techniques of the slump test. Consequently, the occurrence of a Type II error is a potential in this study, as successive repetitions of the slump test could affect the onset of muscle activity and resistance during the slump test. It is therefore important for clinicians to be aware that repeatedly conducting the slump test is a mobilisation technique in itself and numerous repetitions should be avoided where possible.

Overall, the reliability of the examiner at detecting onset of resistance during the slump test with cervical flexion is good in this study; a result which decreased slightly when the spine was extended. However, the matter in which the slump test was conducted in this study is not typical of its true form in a clinical setting. Typically, the slump test with cervical flexion is conducted and whilst the patient remains in this slumped position, the neck or foot of the corresponding limb is moved into extension or plantar-flexion respectively and the clinician looks for differences in symptoms, sensations or range of motion. However, due to the nature of the variables being investigated in this study, particularly onset of muscle activity, the slump test with cervical flexion was conducted separate to that of cervical extension. Whilst recognised as a limitation and not being a true replica of the slump test, this was deemed the only possible way to conduct the slump test with respect to the variables being monitored. Following the conduction of the reliability study, M1 and R1 during the slump test were deemed sufficiently reliable between testing sessions to commence testing on hamstring injured athletes.
4.4 Muscle, pain and resistance onsets, during the slump test in hamstring injured athletes.

4.4.1 Method

4.4.1.1 Participants

Letters of approach were issued to the senior club physiotherapist or sports rehabilitator at various professional and semi-professional football and rugby union clubs in the UK. The therapists were required to respond to the letter as to the clubs willingness to participate. Once a player at the club sustained a hamstring injury, those players who wished to participate were proposed by the therapist and club doctor as suitable candidates. Each participant was also required to complete a consent form (Appendix E), subsequent to reading the participant information sheet (Appendix E).

A total of ten male semi-professional (n=7) and professional (n=3) rugby union players from various clubs\(^2\) volunteered to participate in this study, all of whom presented with a current hamstring strain, as diagnosed by their respective club physiotherapist or sports rehabilitator and club doctor. A professional athlete is one whose full-time occupation is their chosen sport, whilst those of a semi-professional nature receive payment in return for competing and participating in their sport on a part-time basis. The mean age of this cohort at the time of testing

\(^{2}\)Caldy RUFC, Doncaster RUFC, Sedgley Park RUFC
was 24.9±3.3 years (range 20-31 years) and the average length of time from injury occurrence to testing was 18.8±6.3 days (range 13-30 days). Seven of the entire cohort cited a history of hamstring strain, with three of these reporting hamstring injuries to the same limb. Ethical approval was obtained from the Institutes ethics committee (Appendix B), following which; consent was obtained from all participants.

4.4.1.2 Testing Protocol

The slump test, with cervical flexion and extension, was assessed in all injured players of this study, in both limbs. The exact same testing procedure utilised in the reliability study of this chapter was conducted on the injured athletes, with only minor differences; one being that only three trials for both cervical spine components of the slump test was conducted on each leg. Additionally, the injured participant was required to activate a hand-held light-emitting trigger upon experiencing the onset of pain during both cervical spine components of the slump test (Figure 4.2). Onset of pain (P1) was defined in this study as the moment when the least experience of pain, symptoms or sensations is recognised (Coppieters et al., 2002). Onset of pain was assessed in both limbs of the hamstring injured cohort as these athletes may show an altered response to the slump test in the unaffected limb. Considering the spinal cord and nervous tract into the peripheral limbs are one continuous structure (Butler, 2000), there is the possibility that abnormal mechanosensitivity may be present in both limbs of the injured cohort. Onset of muscle activity, resistance and pain was calculated
for each trial of the slump test with cervical flexion and extension using the same analysis procedure as the reliability study. The mean of each variable was then subsequently calculated.

Figure 4.2: The slump test with cervical flexion. The examiner activates a foot trigger upon feeling resistance onset (R1) whilst the patient activates a hand-held trigger for onset of pain (P1) during the cervical flexion component of the slump test as the knee is being passively moved into extension.
4.4.1.3 Data Analysis

Two way ANOVA were utilised to examine the effect of cervical spine position and injury, on the knee angle corresponding to muscle pain and resistance onsets during the slump test in hamstring injured athletes. and also. to determine any differences between the onsets of these four variables during the slump test, for both cervical spine positions. The alpha level for statistical significance was set at $\alpha<0.05$ for both ANOVAs.

Pairwise t-tests with Bonferroni corrections (Corrected alpha level $p<0.008$) were utilised to determine whether statistically significant differences existed between the onset of biceps femoris, semitendinosus, pain and resistance for a given neck position in a given limb.
4.4.2 Results

The mean (± standard error of mean) knee angle obtained in the injured limb during the cervical flexion component of the slump test, were 140.5±5.4°, 148.4±6.1°, 156.5±3.6° and 158.4±3.5° for M1_{BF}, M1_{ST}, P1 and R1 respectively in the injured athletes (Figure 4.3A). Similar values were evident for this particular cervical position in the uninjured limb also for all variables with the exception of onset of muscle activity for biceps femoris (M1_{BF}=147.3±5.4°, M1_{ST}=150.4±2.6°, P1=156.4±1.9° and R1=160.2±2.1°) (Figure 4.3B). M1_{BF}, M1_{ST} and R1 all occurred earlier in range of knee extension in the injured leg compared to the uninjured leg during the cervical flexion component of the slump test (7°, 2° and 2° earlier respectively). Onset of pain occurred at the same knee angle during the slump test with cervical flexion in both limbs.
"M1 (BF)" = Onset of biceps femoris
"M1 (ST)" = Onset of semitendinosus
"P1" = Onset of symptoms/sensations
"R1" = Onset of resistance as determined by the examiner
"degs" = degrees

Figure 4.3: The outcome variables occurrence in relation to knee angle during the slump test with cervical flexion in the injured limb (A) and uninjured limb (B) (n=10).
Cervical extension elicited an increase in the range of knee extension attained in both the injured and uninjured limbs, with the former giving values of $M_{1\text{BF}}=155.7\pm2.2^\circ$, $M_{1\text{ST}}=160.4\pm2.2^\circ$, $P1=163.9\pm2.6^\circ$ and $R1=166.9\pm2.6^\circ$ (Figure 4.4A). In the uninjured limb, the mean knee angles achieved for cervical extension during the slump test were $159.7\pm2.8^\circ$, $160.1\pm3.0^\circ$, $164.8\pm2.2^\circ$ and $165.7\pm1.6^\circ$ for $M_{1\text{BF}}$, $M_{1\text{ST}}$, $P1$ and $R1$ respectively (Figure 4.4B). When the cervical spine was extended, $M_{1\text{BF}}$ occurred $4^\circ$ earlier in range of knee extension in the injured limb than uninjured one, whilst $P1$ and $R1$ occurred $1^\circ$ and $2^\circ$ respectively, earlier in the symptomatic limb. The onset of semitendinosus occurred at the same point in range of knee motion in both limbs during the cervical extension component of the slump test.
"M1 (BF)" = Onset of biceps femoris
"M1 (ST)" = Onset of semitendinosus
"P1" = Onset of symptoms/sensations
"R1" = Onset of resistance as determined by the examiner
"degs" = degrees

Figure 4.4: The outcome variables occurrence in relation to knee angle during the slump test with cervical extension in the injured limb (A) and uninjured limb (B) (n=10).

The two way ANOVA revealed cervical spine position to significantly influence the range of knee extension at which all four variables occurred during the slump test (M1BF, p=0.004; M1ST, p=0.024; P1, p=0.008; P1, p=0.001). The
range of knee extension with which biceps femoris onset occurred in the uninjured leg was on average 12.4±7.8° earlier during cervical flexion of the slump test than when the neck was extended.

A similar trend was evident for all other measurement variables; semitendinosus muscle onset (M1ST) occurred 9.7±8.4° earlier, whilst P1 and R1 occurred on average 7.8±4.1° and 5.6±5.6° respectively, earlier in knee extension range when the cervical spine was flexed in the slump test, compared to the extended position, in the uninjured leg. In the injured limb, cervical flexion resulted in the onset of biceps femoris and semitendinosus occurring on average 15.2±22° and 12.1±23.7° respectively, earlier in range of knee extension, than that which occurred with cervical extension. Onset of pain occurred 8.5±10.2° earlier as a consequence of cervical flexion during the slump test in the injured leg, whilst a similar result was evident for onset of resistance (8.6±4.9°).

From the results, a trend in the sequence of the occurrence of the measurements taken during the slump test is evident, with the onset of muscular activity preceding the subjective reporting of pain and the examiner’s determination of resistance for both cervical positions of the slump test, irrespective of injury status (Figures 4.3A and B: Figures 4.4A and B). In both the injured and uninjured limbs of the hamstring injured athletes, the onset of biceps femoris activity occurred first of all the other variables during knee extension for both cervical positions in the slump test. Semitendinosus activation followed in
relative close succession to \( M_{1BF} \), with the patient always reporting pain (P1) earlier than the examiner feeling resistance (R1); a trend evident during both neck components of the slump test. Whilst this trend was observed in the mean values presented of each variable for the cohort, the sequence of occurrence of these events were seen in 60% of the athletes individual results for cervical flexion of the injured and uninjured limbs and also cervical extension of the uninjured limb, during the slump test. Variable patterns of the occurrence of the four outcome variables in relation to each other were seen for cervical extension of the injured limb, yet in 70% of athletes (7/10), onset of muscle activity preceded pain and resistance onsets for this aspect of the slump test.

Injury was found to have no significant effect on the onset of biceps femoris (p=0.184), semitendinosus (p=0.85), pain (p=0.636) and resistance (p=0.904) during the slump test, irrespective of cervical spine position. Consequently, for the purpose of further analysis, the data for each of the four variables from the injured and uninjured limbs were pooled. A 2-way ANOVA, conducted to determine whether differences exist between the four variables, revealed cervical spine position to have no significant effect (p=0.050) on differences in knee angle which may exist between \( M_{1BF} \), \( M_{1ST} \), P1 and R1, during the slump test. However, a significant difference (p=0.001) was discovered to exist between the knee angle corresponding to muscle activity, pain and resistance onsets during the slump test.
As a consequence of the above findings, it was decided to examine what specific differences lie between each of these four variables for a given cervical spine position in a given limb. Biceps femoris muscle onset \( (M1_{bf}) \) occurred significantly earlier in range of knee extension than semitendinosus \( (M1_{st}) \) \( (p=0.003) \), the patient's reporting of pain \( (p=0.005) \) and the subjective determination of resistance onset by the examiner \( (p=0.003) \) in the injured leg during the slump test with cervical flexion. In the uninjured limb, biceps femoris did not occur significantly earlier during knee extension of the slump test with cervical flexion than semitendinosus \( (p=0.017) \) and pain \( (p=0.05) \), but did occur significant earlier than resistance \( (p=0.006) \).

Non-significant differences existed between semitendinosus onset and \( P1 \) \( (p=0.11) \) and \( R1 \) \( (p=0.06) \) in the injured leg during cervical flexion. Also, in the uninjured limb \( M1_{st} \) did not occur significantly earlier in range than \( R1 \) \( (p=0.016) \) and \( P1 \) \( (p=0.14) \) during the cervical flexion component of the slump test. No significant differences between pain and resistance onset during the slump test with cervical flexion in the injured \( (p=0.11) \) and uninjured \( (p=0.04) \) limbs were seen.

During the cervical extension component of the slump test in the injured limb, \( M1_{bf} \) occurred significantly earlier in knee extension range than \( M1_{st} \) \( (p=0.001) \) and \( R1 \) \( (p=0.004) \), but not for \( P1 \) \( (p=0.02) \). In the uninjured limb, no significant differences were evident between \( M1_{bf} \) and \( M1_{st} \) \( (p=0.63) \), \( P1 \)
(p=0.03) and R1 (p=0.03) during the slump test with cervical extension. M1ST did not occur significantly earlier than R1 in both the injured (p=0.03) and uninjured (p=0.04) limbs for this particular component of the slump test. Similarly, no significant differences were discovered between the onset of semitendinosus and the patients reporting of symptom onset during cervical extension of the slump test in the injured (p=0.26) and uninjured limbs (p=0.06). No statistically significant difference was discovered between pain and resistance onset during the slump test with cervical extension for the injured (p=0.37) and uninjured (p=0.47) limbs.
4.4.3 Discussion

The aim of this study was to evaluate the onset of muscle activity, pain and resistance during the slump test, in athletes with clinically diagnosed hamstring strains. One of the primary findings of this investigation was the order in which these measurements actually occurred during the slump test. Biceps femoris was the first of the hamstring muscles to activate during both cervical positions of the slump test, in both limbs, whilst onset of resistance occurred last of all variables. Structural differentiation by means of altering the cervical spine position had a significant effect (p<0.05) on each of the four variables measured during the slump test, whilst injury had no statistically significant effect (p>0.05) on muscle, pain or resistance onsets.

Structural differentiation caused M1BF, M1ST, P1 and R1 to occur earlier in range of knee extension during cervical flexion than extension of the slump test in this study concurring with previous research who reported structural differentiation to cause the measurements typically taken during neurodynamic tests to occur significantly earlier in the range of the moving joint (Johnson and Chiarello, 1997; van der Heide et al., 2001; Herrington et al., 2008). Cervical flexion caused an earlier onset of resistance (R1) during the slump test, in the injured and uninjured limbs (8.5° and 5.6° respectively) in this study; values similar to that of Herrington et al. (2006) and Johnson and Chiarello (1997) who cited decreases in knee extension ranging from 5.4° to 6.6° during this neurodynamic test also. Structural differentiation affected not only the onset of
resistance as detected by the examiner during neurodynamic tests but also the
onset of pain (P1). This study demonstrated P1 to occur on average 7.8° and
8.5° earlier in range of knee extension for the uninjured and injured legs
respectively, when the cervical spine was flexed during the slump test. These
values are relatively close to those obtained by Boyd et al. (2009) for the straight
leg raise (SLR), whereby ankle dorsi flexion caused 5.5° less hip flexion
compared to when the ankle was plantar flexed. Van der Heide et al. (2001)
reported the onset of pain during an upper limb neurodynamic test to occur 19.2°
earlier as a result of structural differentiation (contralateral cervical side flexion
(CCSF)) than when the spine was in a neutral position; a significantly larger value
when compared to the injured (8.5°) and uninjured limbs (7.8°) in this study and
the work of Boyd et al. (2009).

The earlier onset of pain during the slump test as a consequence of
cervical flexion potentially occurs due to the effect this manoeuvre has on the
neural tissues of the body. Inman and Saunders (1942) and Smith (1956)
demonstrated cervical/trunk and hip flexion individually to cause migration of the
cervical, thoracic and lumbar nerve segments of varying magnitude. Combining
these manoeuvres, such as which occurs during the slump test, would place
considerably more strain on the spinal cord and its expansions, potentially
provoking intense symptoms in the patient, with perhaps an early onset of pain.
A primary difference between the findings reported in this study and van der Heide et al’s (2001) work may lie in the operational definition of pain onset (P1). Both this study and the work of Boyd et al. (2009) utilised very similar definitions for instructing participants in determining P1, which may partially explain why the results are relatively similar, despite different neurodynamic tests. Boyd et al. (2009) defined P1 as the point when the subject experienced the first onset of any symptoms; a definition similar to this study whereby P1 was regarded as the point when the least experience of pain, symptoms or sensations was recognized by the subject (Coppieters et al., 2002). The operational definition for P1 utilised by the van der Heide et al. (2001) was defined as the first onset of pain experienced by the subject. However, pain is not the only symptom exclusive to neurodynamic testing, as the majority of participants in Boyd et al’s (2009) research used words such as “stretch”, “tight/tension” and “ache” to describe the sensations experienced during the SLR, irrespective of the ankle position. Pain was actually reported infrequently by the 20 healthy participants of Boyd et al’s (2009) study.

Van der Heide et al. (2001) regarded pain to be a naturally occurring event during these tests; a conclusion possibly reached due to the inclusion of subjects into the study who experienced pain in all trials of the neurodynamic test. An element of bias is therefore evident in this study as on average, almost 40% of subjects did not experience pain during neurodynamic testing and were therefore excluded from van der Heide et al’s (2001) results. Removing the focus of the
definition for P1 to encompass a wider range of sensations, such as ache or stretch rather than focussing on pain, would have increased the sample size of van der Heide et al’s (2001) study, in addition to increasing its applicability to the general population.

Onset of pain and resistance are not the only variables which are affected by structural differentiation during neurodynamic testing; this study demonstrated cervical flexion during the slump test to have a significant effect \( (p<0.05) \) on the knee angle corresponding biceps femoris and semitendinosus onsets in both limbs. Van der Heide et al. (2001) reported the onset of muscle activity for the Trapezius muscle to occur on average 12.2° earlier in range of elbow extension during an upper limb neurodynamic test, when contralateral cervical spine side flexion (CCSF) was the structural differentiator. Cervical flexion caused a decrease in knee extension in the injured limb for biceps femoris in the injured (15°) and uninjured (12.4°) limbs in this study. Similarly, onset of semitendinosus occurred earlier in the injured (12.2°) and uninjured limbs (9.7°); all findings relatively similar to van der Heide et al’s (2001) results.

The reason as to why moving a joint as remote as the cervical spine during the slump test causes earlier activation of biceps femoris may be due to the anatomical arrangement of this muscle, which attaches indirectly to the spine via the thoracolumbar fascia and sacrotuberous ligament (Vleeming et al., 1995). Coupling the fact that the thoracolumbar fascia has superior attachments with the
rhomboid muscles and to the tendons of splenius cervicis and capitis (Barker and Briggs, 1999) and therefore permits force transmission between the upper and lower quadrants of the body (Vleeming et al., 1995), cervical flexion during the slump test could increase the force transmitted to the lower extremity, via the fascia and biceps femoris. However, as semitendinosus does not have the same diverse attachments as biceps femoris, it limits the explanation of the fascia of the thoracic and lumbar spine being responsible for structural differentiation causing earlier onset of muscle activity. An alternate suggestion as to why cervical flexion during the slump test causes earlier onset of hamstring muscle activity, particularly in the injured limb, may be related to these muscles preventing any excess strain being placed on the local peripheral nerves during this test.

Neurodynamic tests affect the strain induced on nerves, with each sequence of a neurodynamic test causing tension over a greater portion of the nerve, rather than the segment closest to the moving joint (Coppieters et al., 2006a). Coppieters et al. (2006a) demonstrated the dissipation of tension generated during the SLR along the course of the sciatic nerve and its expansions. Hip flexion and ankle dorsi-flexion not only caused significant increases in strain in the tibial nerve at the knee and the sciatic nerve, but also in the tibial nerve at the ankle in Coppieters et al's (2006a) study. It is likely that the dissipation of strain in the nerve occurred to prevent excess strain within a specific nerve segment in an attempt to prevent injury. With increasing movement
and therefore strain occurring within the sciatic nerve during the slump test, particularly with cervical flexion, the nerve in isolation may not be a sufficient enough mechanism to prevent injury to itself; particularly if it is already sensitive to extreme movements. Consequently, the local muscular system may activate earlier to pre-empt any increases in strain to the nerve; thereby decreasing the risk of injury.

The ability of the muscular system to innately protect the more vulnerable nervous system during neurodynamic testing is a feasible theory. Balster and Jull (1997) reported muscle activity to continually increase with each successive stage of a neurodynamic test for the upper limb (Brachial Plexus Tension Test). Once the initial stage of the clinical test was applied, activity within the upper trapezius significantly (p<0.05) increased above baseline levels. As each subsequent stage of the BPTT occurred, such as elbow extension and contralateral cervical lateral flexion, a corresponding increase in activity of the upper trapezius was evident. The authors suggested that the upper trapezius acts as a protector for the nervous system, as with each manoeuvre applied during the neurodynamic test, all factors which increase the tensile load on the peripheral nerves, enhanced muscular activity concomitantly occurs.

Boyd et al. (2009) concur with these findings having discovered the number of muscles activated between P1 (onset of pain) and P2 (maximum tolerated pain) increased during the SLR with varying ankle positions. At P1
during the SLR with plantar flexion (SLR-PF), only Rectus Femoris was activated. However, then the hip was flexed to the point of maximum pain (P2), six more muscle had activated before this point (vastus medialis, tibialis anterior, soleus, medial gastrocnemius, biceps femoris and gluteus maximus). Likewise, additional muscles were activated between P1 and P2 during the SLR with ankle dorsiflexion (SLR-DF) with vastus medialis, tibialis anterior, soleus and semitendinosus activated at the former point and rectus femoris and medial gastrocnemius being activated prior to P2, alongside those muscles which were initially active at P1. Boyd et al. (2009) promoted the theory of the muscular system acting as a protective mechanism for the nervous system.

Interestingly, whilst the SLR was conducted passively in Boyd et al’s (2009) study, this does not explain why rectus femoris, vastus medialis and tibialis anterior, all muscles located on the anterior thigh and lower limb, were activated. There is no explanation, based on the anatomical location of these muscles, as to how they could protect the sciatic nerve from excess strain. It is possible that as the knee was unsupported during the SLR, that the subjects were assisting in maintaining knee extension by contracting the quadriceps. The authors do not offer any explanation as to why these muscles were active during the SLR, despite patients being instructed to remain relaxed.

Whilst muscle activity appears to be an automatically occurring event during neurodynamic tests, disagreement exists amongst authors as to what the
onset of muscle activity actually represents, with one suggestion being that pain is strongly correlated with onset of muscle activity (van der Heide et al., 2001), whilst others disagree with this theory (Balster and Jull, 1997; Boyd et al., 2009). This study discovered no significant difference ($p<0.008$) to exist between biceps femoris and symptom onset during both cervical spine positions of the slump test in the uninjured limb and the cervical extension component in the injured limb. Differences between the onset of semitendinosus and pain were also non-significant for each cervical spine position of the slump test, in both limbs. These findings imply that the onset of biceps femoris and semitendinosus muscles occurred as a consequence of the onset of symptoms experienced by the cohort.

However, this does not hold true for the injured limb during the slump test with cervical flexion, as the onset of biceps femoris activity occurred significantly earlier than symptom onset in the cohort. This finding concurs with Boyd et al. (2009), who cited no correlation between the increased muscle activity evident during the SLR and the increasing symptom intensity cited by participants. Balster and Jull (1997) reported an almost identical finding for the BPTT, with no correlation evident between the intensity of pain perceived during the clinical test and the magnitude of upper trapezius muscle activity. The research of van der Heide et al. (2001) however, disagrees with the aforementioned authors having reported moderate/good correlation between the onset of pain (P1) and the onset of trapezius activity for both a neutral cervical spine position and contralateral side flexion (i.e. structural differentiating manoeuvre).
Balster and Jull (1997) and Boyd et al. (2009) concur that an increase in muscular activity during neurodynamic testing does not necessarily occur as a result of pain and may in fact be a response to sensations other than pain; a factor van der Heide et al. (2001) did not take into account having excluded individuals who did not report pain during neurodynamic testing. Despite the disagreement amongst authors as to whether the muscle response during neurodynamic tests is as a consequence of pain (Balster and Jull, 1997; van der Heide et al., 2001; Boyd et al., 2009), all three researchers concur that the nervous system is protected from excess tensile forces during these clinical tests by activation of the surrounding muscles.

Ultimately, deriving a conclusion based on the findings of this study is difficult. Whilst biceps femoris did not predominantly activate in response to symptom onset (P1) in the hamstring injured population during the slump test with cervical flexion, semitendinosus did; an unsurprising finding considering biceps femoris activated significantly earlier (p<0.0008) than semitendinosus in the injured leg, during this manoeuvre. The differences in onset of biceps femoris and semitendinosus in this study, particularly during the cervical flexion component of the slump test in the injured limb, is an intriguing one, particularly considering both muscles are representative of the generic hamstring muscle group. The anatomical make-up of both these muscles however, is quite different as biceps femoris' comprises of two heads; a long and short one; the latter being
supplied by the common peroneal nerve which is a different nerve supply to the remaining hamstring muscles and the long head of biceps femoris (Katrji, 1999, Yuen and So, 1999). With two different nerve supplies, therein lies the possibility that asynchronised contraction of the two heads of biceps femoris can occur, potentially explaining why this muscle accounts for 53-80% of all hamstring injuries (Armfield et al., 2006, Malliaropoulos et al., 2010, Woods et al., 2004).

The long head of biceps femoris is the most common injury site in athletes with a clinically diagnosed hamstring strain (Silder et al., 2008). In those participants with evidence of hamstring injury, when examined 5-23 months post injury, Silder et al. (2008) discovered atrophy of the long head of biceps femoris on MRI scan, with concomitant hypertrophy of the short head. The authors surmised that the asymmetry in muscle size occurred due to an exercise-induced compensation for the atrophy of the long head. It is possible that these differences between the long and short heads of biceps femoris lead to asynchronised contraction of muscle, ultimately leading to differences in the gross activation timing of this muscle compared to semitendinosus, during the cervical flexion component of the slump test. No empirical evidence however exists as to the contraction properties of biceps femoris and whether discrepancies exist in onset and intensity of activation between the long and short head of this muscles; this theory is therefore speculative in nature.

It is possible that in the injured leg, biceps femoris attempts to protect both itself and the local nervous system from excess strain during the knee extension
phase of the slump test with cervical flexion; a position which theoretically increases the strain within the sciatic nerve. With injury to the actual hamstring muscles themselves, terminal extension of the knee joint may be limited due to heightened sensitivity of the muscle spindles to stretch during the knee extension component of the slump test. Resultant scar tissue of an actual muscle injury has the potential to increase the overall mechanical stiffness of the myofibrous tissue it replaces, causing the myofibers to have to lengthen significantly more to achieve pre-injury levels of knee extension (Silder et al., 2008). In a hamstring injured athlete with a developing scar and wound site vulnerable to stretch, knee extension could be an adverse movement to conduct in this particular type of patient. Consequently, the knee extension component of the slump test may have caused earlier activation of biceps femoris, particularly during the cervical flexion component of the test when biceps femoris may already be pre-tensed, to prevent further stretch within the generic hamstring muscle group. This is only speculative however, as no imaging investigations were undertaken in this study to confirm or refute the presence of muscle damage in the hamstrings; therefore it is unknown whether any muscular damage actually existed in the injured cohort of this study.
4.3.4 Limitations

One of the primary limitations of this study is the limited sample size, with only 10 injured athletes recruited. Despite repeatedly contacting the participating clubs throughout the duration of the study, reminding them of the need for hamstring injured athletes for this study, it is possible that not all hamstring injuries from each club was tested. Upon reflection, a larger sample size could have been recruited from a variety of different sports, of differing competition levels. As with the previous study, semi-professional and professional clubs were approached in an attempt to maximise the incidence of hamstring injury; again to enhance the sample size, the inclusion of amateur athletes may have been beneficial.

Upon reflection of this study, the use of radiological investigations, such as MRI or ultrasound, would have enabled a definitive diagnosis of hamstring muscle strain within the cohort. Whilst the findings of this study have provided information on the interactions of the local muscular system, pain and resistance during the slump test in hamstring injured athletes, confirming or refuting the presence of muscle damage to the hamstrings would have enhanced this study. However, as all the testing sessions were conducted at each participating club, a portable ultrasound machine would have been required and this was a tool not available within this research project.
Despite the EMG electrode arrangements being targeted at the long head of biceps femoris (Cram and Kasman, 1998), the possibility of obtaining cross-talk from the short-head of the same muscle or semitendinosus, is relatively high as all muscles lie in such close proximity to each other. Cross-correlation analysis of EMG signals is not, according to Lowery et al. (2003) a suitable means of quantifying EMG signal cross-talk and therefore was not undertaken in this study. To differentiate the onset of muscle activity between the long and short heads of biceps femoris, needle electrodes would be ideal to use to determine any asynchronicity between the activation of these muscle segments. However, invasive EMG via needle electrodes of the muscles in the posterior thigh is not feasible during the slump test due to the patient having to remain seated with the thigh fully supported. Consequently, despite the risk of cross-talk between the two heads of biceps femoris and the semitendinosus muscles, surface EMG was the most suitable method for investigating muscle onset in this study.

4.3.5 Summary

Muscle activity, pain and resistance onsets during the slump test in hamstring injured athletes was investigated in this study and displayed a variety of results; the primary one being that biceps femoris activates first of all the variables measured during this neurodynamic test, irrespective of the cervical spine position. Biceps femoris actually activated significantly earlier than the
semitendinosus during the cervical flexion component of the slump test in the injured limb. Onset of resistance persistently occurred last of all four variables throughout the slump test and appeared to occur in response to heightened activation of the biceps femoris muscle, as opposed to onset of this muscle.

To progress from the current study, it was decided to investigate the movement of the sciatic nerve in the posterior thigh during the slump test using ultrasound to intrinsically examine the effect a radiological-confirmed hamstring strain has on the longitudinal excursion of the nerve. As the subsequent study was entirely laboratory based, ultrasonography was available to examine the posterior thigh in injured athletes for evidence of muscle damage.
Chapter 5

Study 3

The effect of hamstring injury on the longitudinal excursion of the sciatic nerve during the slump test: A preliminary investigation.

5.1 Introduction

Peripheral nerve excursion occurs in response to joint movement and in the direction of the moving joint (Babbage et al., 2007, Boyd et al., 2005, Coppieters et al., 2006a, Dilley et al., 2003, Dilley et al., 2007). Whilst neurodynamic testing and its effect on nerve excursion, both longitudinal and transverse has been investigated in-vivo, primarily in the upper limb (Dilley et al., 2003; Dilley et al., 2007; Hough et al., 2007), the slump test has primarily been neglected in research into this area. Consequently, an initial aim of this study was to determine if convergence of the sciatic nerve occurs in the slump test, as appears evident in the upper limb neurodynamic tests in healthy individuals (Dilley et al., 2003; 2007). It is anticipated that the sciatic nerve in the posterior thigh will move in a distal direction, as a consequence of ankle dorsi-flexion during the slump test.
Repeated hamstring injury can produce inflammation and scarring within the tissues (Shacklock, 2005a); the consequence being interference in the movement of the sciatic nerve (Turl and George, 1998). A positive slump test was discovered in athletes with recurrent hamstring strains by Turl and George (1998) leading the authors to conclude that neural mechanosensitivity occurred as a consequence of secondary nerve damage resulting from intramuscular adhesions in the hamstring muscles. It was postulated that scarring of the muscular tissue following injury can tether a nerve and render it less mobile than its pre-injury state (Turl and George, 1998; Shacklock, 2005a). Whilst scarring is a natural occurring event in recovery from muscle injury (Jarvinen et al., 2005), the effect of muscle strain on peripheral nerve movement is to-date unknown. Consequently, longitudinal nerve excursion in hamstring injured athletes during the slump test was investigated in this study.

High resolution, high quality ultrasound permits in-vivo examination of peripheral nerve excursion during neurodynamic tests (Hashimoto et al., 1999, Dilley et al., 2003; Dilley et al., 2007; Hough et al., 2007). To achieve optimum results using ultrasound to investigate tissue excursion, a high frequency linear array probe is advocated (Bradley and O'Donnell, 2002; Beekman and Visser, 2004) as it accommodates the linear and oval shape of many structures of the musculoskeletal system (Hashimoto et al., 1999). A linear array transducer also permits the sonographer to view the injured or affected structure in addition to the anatomical structures in the vicinity of the injury site, due to it providing a wide
field of view (Hashimoto et al., 1999). All images of the sciatic nerve using ultrasound can be attained using high-frequency linear array transducers ranging from 5.0MHz to 15MHz (Graif et al., 1991, Beekman and Visser, 2004, Ellis et al., 2008).

Peripheral nerves appear tubular in shape (Fornage, 1988; Beekman and Visser, 2004) comprising of multiple hypoechoic bands separated by hyperechoic lines (Beekman and Visser, 2004) on longitudinal ultrasound scans. In a longitudinal image, nerves and tendons can appear similar as they are both tubular, striated structures (Hough et al., 2000a) and therefore prior identification of the sciatic nerve by transverse imaging is recommended (Sites et al., 2004). To ensure the structure being traced is actually a nerve, when moving the probe cranially; the appearance of the nerve should be constant whilst the surrounding structures change constantly (Tsui and Finucane, 2006).

There are several considerations to take into account when using ultrasound to examine nerve excursion during a neurodynamic test. Deeply situated nerves are often more difficult to visualise, as are those who are surrounded by fat as both these tissues are very similar upon imaging (Beekman and Visser, 2004). Nerves situated under bony structures can also be problematic for the sonographer due to acoustic shadowing (Beekman and Visser, 2004). To minimise errors when conducting ultrasonography on peripheral nerves, Beekman and Visser (2004) recommend minimising the
pressure on the skin throughout the examination as excess pressure could deform a nerve, particular those of a superficial location. Additionally, correct positioning of the probe is vital in high-resolution sonography, as should the ultrasound beam not hit the nerve at a perpendicular angle, it may be falsely interpreted as being hypoechoic (Beekman and Visser, 2004). To obtain an optimal signal, the aforementioned authors recommend constant steering of the probe in order to remain as close to the perpendicular angle as possible.

Despite the aforementioned concerns of Beekman and Visser (2004), high-frequency ultrasound was regarded as the most suitable tool for examining the longitudinal excursion of the sciatic nerve during the slump test in this study as it permitted real-time images of the movement of the nerve to be collected during the slump test. Ultrasonography was also used in this study to confirm or refute the presence of muscle damage within the hamstring muscle group. Whilst MRI may be regarded as more appropriate to use in diagnosing muscles strains as it is highly reliable and not operator-dependant (Schneider-Kolsky et al., 2006), ultrasound is regarded as a more cost-effect method for diagnosing acute hamstring injuries (Askling et al., 2000, Connell et al., 2004). The cost and availability of MRI may preclude the use of this tool in the routine assessment of muscle injuries (Schneider-Kolsky et al., 2006); therefore ultrasound may be a more cost-effective tool to utilise in injuries which have high occurrence and recurrence rates, such as hamstring muscle injury.
Koulouris and Connell (2006) deem ultrasound to be a sensitive imaging modality when oedema and blood products are present, such as which occur in muscle strains. However, the aforementioned authors concede that in very minor muscle strains, the diagnosis of muscle strains via ultrasonography may be difficult as the low echogenicity of the injury site contrasts poorly with the low echotexture of skeletal muscle. Nonetheless, due to the easy accessibility to ultrasonography, it was the preferred investigatory tool to confirm or refute the diagnosis of hamstring strains in this study.

Two methods for analysing longitudinal nerve excursion in-vivo exist; Spectral Doppler and frame by frame cross correlation algorithm. The former analysis method involves converting the ultrasound images into Tagged Image File Format (TIFF) before being analysed. The phases of joint motion examined are traced by an examiner on each Spectral Doppler plot, which yield the velocity time integrals (VTIs). These VTIs represent the amount of median nerve excursion during each movement sequence (Hough et al., 2000b). Single operator test-retest reliability of median nerve motion with spectral Doppler sonography produced excellent results (r=0.92) in Hough et al's (2000b) study. The test-retest reliability however, is only applicable to the image acquisition, processing and VTI calculation as all data was collected during one session and the position of each participant did not change within that session. The Doppler technique, according to the aforementioned authors, can measure nerve excursion at any location where the nerve is easily identified; yet it can be
dependent on the nerve’s size and anatomical course. Hough et al. (2000b) suggest that Doppler technique may not be the most appropriate choice in nerve segments which undergo significant transverse movement, such as that which occurs in the popliteal crease by the sciatic nerve (Ellis et al., 2008), as the nerve may move outside the Doppler sample volume and be replaced by an alternative structure. The authors conclude that the Spectral Doppler technique can be a reliable tool for evaluating longitudinal nerve excursion.

Frame by frame cross-correlation algorithm, developed by Dilley et al. (2001), involves analysing nerve movement between adjacent frames in an ultrasound image. With each image converted to text format, the macro calculates the correlation coefficient \( r \) between the pixel grey levels for a selected region of interest (ROI), in two adjacent frames. The ROI corresponds to the area of interest to be measured on the ultrasound image of the nerve. The dimension and position co-ordinates of the ROI are entered into memory, following which, in the compared frame, the co-ordinates of the ROI are offset along the horizontal image plane and are shifted one pixel at a time. The correlation coefficient \( r \) is calculated for each individual pixel shift, and the pixel shift which produces the maximum correlation coefficient corresponds to the relative movement between the two frames (Dilley et al., 2001).

Dilley et al. (2001) demonstrated good repeatability for using the frame by frame cross-correlation algorithm in evaluating median nerve movement within
one testing session. The average median nerve movement varied by only 10% between trials on the same day, a finding which was discovered to be non-significant, leading the authors to conclude that the frame by frame cross correlation algorithm is reliable in repeat trials for quantifying longitudinal excursion. Dilley et al. (2001) also examined the validity of the cross correlation algorithm for measuring nerve excursion by using phantom controls, whereby string and isolated avian sciatic nerve were placed in a water bath containing water or saline and the bath was moved a pre-determined distance (1-15mm). The authors imaged the phantoms in longitudinal section using ultrasound and subsequently examined them using the frame by frame cross correlation algorithm. The authors reported similar results between the two different phantoms (string and nerve) and the correlation algorithm measured longitudinal movement consistently during each test period, particularly at higher velocities. The authors demonstrated the ability of the frame by frame cross correlation algorithm to reliably and effectively measure longitudinal excursion of two different structures.

Whilst Doppler imaging is advantageous at measuring nerve excursion at locations where the nerve is clearly imaged (Hough et al., 2000b), it is restricted to longitudinal movement and requires a steep beam-to-nerve angle (45°-60°) thereby minimising its ability to measure nerve movement in locations where the nerve is horizontal (Dilley et al., 2001). Cross-correlation however, accurately measures horizontal movement of structures with an angle of <20°, in addition to
tracking vertical movement across the image plane. Doppler tissue analysis according to Dilley et al. (2001) is limited by the lowest velocity at which the Doppler can reliably measure tissue movement; a factor the cross correlation algorithm is not confined to.Frame by frame cross correlation ultimately allows the analysis of longitudinal movement of nerve, tendon and muscle at various anatomical locations allowing all of these structures to be imaged simultaneously within one image (Dilley et al., 2001). This study utilised a cross-correlation algorithm to quantify the longitudinal excursion of the sciatic nerve in the mid posterior thigh in athletes with posterior thigh pain, during the slump test.

5.2 Aim

The aim of this study was to examine longitudinal sciatic nerve excursion in the posterior thigh during the slump test in athletes presenting with clinically diagnosed hamstring strains.

This study examines the direction and magnitude of longitudinal movement of the sciatic nerve in the posterior thigh, during the slump test in athletes presenting with hamstring injury, as diagnosed by their medical team. The reliability of using a cross correlation algorithm to examine longitudinal excursion of the sciatic nerve, within one session, was examined in healthy individuals prior to testing injured athletes.
5.3 Method

5.3.1 Participants

Participants with a clinically diagnosed hamstring strain were recruited for this study. The senior club physiotherapist or sports rehabilitator at various professional and semi-professional football and rugby union clubs in the U.K. was contacted in writing regarding interest in partaking in this study. The offer to participate was also extended to the Clinical Lead of the physiotherapy department within the English Institute of Sport in the North West of England and was one which was accepted. Additionally, via their professional body BASRaT (British Association of Sports Rehabilitators and Trainers) over 100 graduate sports rehabilitators were approached regarding their willingness to act as ambassadors to this study for patients within their respective sports clubs and clinics.

Once an athlete sustained a hamstring injury as determined by their respective practitioner and club or institute doctor, a participant information sheet was issued to the patient (Appendix G), upon which, the injured athlete made a decision as to whether to partake or not. Each participant was required to complete a consent form (Appendix G) prior to any testing commencing. Convenience sampling was utilised for the uninjured group in the reliability study and individuals who were interested in partaking in this study were also administered with a participant information sheet and a consent form.
A total of three hamstring injured male athletes participated in this study having sustained an injury to the posterior thigh on average 13 days prior to testing. The mean (±standard deviation) age of the injured cohort was 23±2.6 years, and the left leg was injured in two of the three cases. All hamstring injuries were initially clinically diagnosed by each player’s respective practitioner. An absence of bruising and swelling in the posterior thigh since injury occurrence was evident in all cases. Two of the participants competed at semi-professional level rugby union\(^3\), whilst one was involved in 1500m track and field.

Six healthy, asymptomatic males (30±9.6 years) volunteered to participate in this study, whereby the reliability of the testing procedure was evaluated. No history of major surgery or trauma to the hip, lumbar spine, buttock and posterior thigh were evident in this group. The presence of symptoms indicative of injury to the sciatic nerve, such as tingling or weakness, were also absent within this cohort. Prior to undertaking this study, ethical approval (Appendix B) was obtained from the University of Salford’s ethics committee. Consent was obtained from all subjects used in this study, prior to commencement of the testing session.

5.3.2 Diagnosis of hamstring strain

To confirm the presence or absence of a muscle tear within the hamstrings of the injured cohort, an experienced ultrasonographer scanned the

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\(^3\) Caldy RUFC. English Institute of Sport, Sedgley Park RUFC.
area of symptoms or pain, as indicated by the participant, both longitudinally and transversely. The ultrasonographer diagnosed the site of injury as having muscle damage, via the presence of haematoma, as is a naturally occurring event during the healing process of an injured muscle (Jarvinen et al., 2005). Grade 1 muscle tears typically present on ultrasound as flame shaped hypoechoic bundles (Hashimoto et al. 1999).

5.3.3 Testing Procedure

The testing protocol used for this study particularly that of the patient set up was adapted from Ellis et al's (2008) research. An isokinetic dynamometer (KinCom) was utilised in passive mode to conduct a modified version of the slump test. Subjects were seated onto the dynamometer with the back rest upright. The hip and knee joints were positioned in 90° and 50° flexion respectively, using a hand held goniometer, as per Ellis et al. (2008). The foot was placed in a plantar-dorsi flexion support of the dynamometer, in a neutral position. The non-tested leg was placed on a support adjacent to the dynamometer. No straps were placed across the hips, legs or foot so as to not constrain the subject during the slump test.

The slump test involved the subject sitting in the above position and then actively inducing thoracic spine flexion whilst their hands rested on the anterior thighs (Figure 5.1). The subject was then asked to either place the cervical spine in flexion (chin to chest) or extension (look upwards) whilst the ankle was moved
through its range of motion by the dynamometer. The ankle movements were therefore the structural differentiating manoeuvres in this particular study and involved the dynamometer moving the ankle through a range of 20°, going 10° either side of the neutral position of the ankle at a speed of 10°/sec. The joint positions of the ankle were measured using a hand held manual goniometer.

Figure 5.1: Subject and equipment set-up for ultrasound imaging the sciatic nerve during a modified slump test.

The neutral position of the ankle was initially set at 90° for all subjects. However, it was noted in several subjects that moving the ankle 10° into dorsiflexion from this point caused the heel to lift from the ankle support or often, the knee to undergo a valgus strain. To ensure minimal movement of the ankle and
knee, these subjects were taken to the point of dorsi-flexion whereby none of the aforementioned problems occurred and then moved 20° in the opposite direction. Consequently, all subjects went through a full 20° of dorsi-flexion and plantar-flexion, with no movement of the knee or lift-off of the heel occurring.

No over-pressure was applied at the thoracic or cervical spine due to an inaccessibility of providing this overpressure amongst the numerous pieces of equipment surrounding each subject. It was also unviable to use a strap to maintain the thoracic spine in flexion, as was used in previous studies within this thesis, due to the stand for the dynamometer chair being centrally placed and the strap being unable to fit directly under the participant. Placing a strap in front of the stand and around the patient's thoracic spine brought the subjects trunk and lumbar spine forward into considerable flexion, with the angle of the hip being compromised. Consequently, no overpressure was applied to any subjects throughout this particular study. The potential effect of not applying overpressure was discussed relative to Gabbe et al's (2005) study in Chapter 3 (page 109); it possibly lessens the effect of tensioning the nerve as it is dependent on the individual themselves as to the extent of thoracic and cervical flexion.

Whilst maintaining the slumped position, with the cervical spine in either flexion of extension, the dynamometer then moved the ankle passively, at a speed of 10°/second, from full dorsi-flexion to full plantar-flexion and vice versa, ensuring one full trial of ankle dorsi-flexion and plantar flexion was collected.
Three trials for each cervical spine position, on each leg, were collected for the injured cohort. The dominant leg only (right leg in all participants) was measured in the control group. Randomisation of the cervical spine position and limb tested was undertaken for each injured subject, whilst the cervical spine order of testing was randomised for the control group only. Ultrasonography was utilised to image the movement of the sciatic nerve in the posterior mid-thigh, throughout all trials.

B-mode real-time ultrasound scanning (Mylab 70, Esaote Italy) was performed using a 7.5MHz, 40mm linear array transducer. The sciatic nerve was scanned, by the author of this thesis, in the longitudinal plane in the mid-posterior thigh only, proximal to the site where the nerve splits into the common peroneal and tibial nerves. The author was blind to the outcome of the ultrasonographer’s diagnosis of hamstring injury presence or absence, at the time of testing and until the completion of analysis of the ultrasound images. The posterior mid-thigh was deemed the most suitable site for investigating longitudinal nerve excursion in this particular study, as it was anticipated that transverse movement of the sciatic nerve would be reduced in more proximal areas of the thigh where the nerve is situated deeper than in the popliteal crease (Ellis et al., 2008).

The sciatic nerve was imaged in the proximal posterior thigh; the location of the structure being identified in transverse view initially, before examining the nerve longitudinally, during the testing protocol. To ensure the probe location was
located above the nerve split, the transducer was moved caudally and cranially along the posterior thigh, whilst ensuring the sciatic nerve was continually visualised. When the location of the split within the nerve was identified, the probe was moved proximal to this, and the best possible image was obtained of the sciatic nerve. Following this, the location of the probe was marked on the posterior thigh, after which, a thin wire was taped across the centre of the marked area for the probe. This was to allow the examiner, upon data analysis, to determine if the probe moved during the testing procedure, as it was assumed the wire should not move during the slump test.

The probe was then placed across the wire, ensuring the nerve was clearly visualised whilst the wire was permanently in the image. The isokinetic dynamometer was connected to a computer, via a displacement lead, which recorded the displacement of the ankle during the dorsi-flexion and plantar-flexion movements of the slump test. One of two channels constructed in Testpoint for this study was dedicated to displaying the displacement curve from the isokinetic dynamometer. The second channel was specifically allocated to an external trigger which allowed synchronisation of the ankle movement between the dynamometer and the ultrasound machine. The trigger was connected directly to the ultrasound machine, whereupon activation, a spike appeared in the ECG channel of the ultrasound machine (Figure 5.2). The trigger also appeared in a channel in Testpoint, allowing the examiner upon data analysis, to determine
the precise moment in time the ankle moved from plantar-flexion to dorsi-flexion, and vice versa.

5.3.4 Data Analysis

Preparation of the video clips was undertaken using Quintic (Version 17.0) software. The time between the trigger being activated and the start of either the ankle plantar flexion or dorsi-flexion movement was calculated. This time was
then converted into frames per second, so that when viewing the ultrasound image in Quintic, the frame number corresponding to the start of the movement was identified.

The time of the ankle movement, either dorsi-flexion or plantar-flexion, in seconds was determined to enable the calculation of the number of frames for each movement. Consequently, when reviewing Quintic and the ultrasound image again, the exact image of isolated dorsi-flexion or plantar-flexion was obtained. Knowing the number of frames in each ankle movement of an image, and the frame number by which the movement started, Quintic allowed each ultrasound image to be cropped to include ankle dorsi-flexion or plantar-flexion for the selected trial in preparation for analysis using the cross-correlation algorithm. An adaptive block matching algorithm using cross-correlation to quantify nerve movement in-vivo was developed for this study by a technical expert and is similar to that developed by Dilley et al. (2001). This algorithm continually adapts the target region of interest throughout the entire nerve movement to enable best matching to be achieved.

Each ultrasound image of one ankle movement for each trial of the slump test was uploaded to MATLAB (2010 version) for frame by frame analysis using the cross-correlation algorithm. For each image, the scale measurement was set relative to the depth of the ultrasound image. The threshold correlation value was set at $r=0.60$ for each trial, meaning that only successive images which had a
minimum correlation of $r=0.60$ between the pixel grey levels for the ROI were included. A block matching with normalised cross-correlation was used and the tracking method was adaptive. The region of interest (ROI) was set at 5x5 pixels and selected on the ultrasound image. Each individual ultrasound trial was analysed using the cross-correlation algorithm.

To accommodate for any ultrasound probe movement which may have occurred whilst imaging during the slump test for each image, an echo absorptive marker (i.e. wire), which had been placed on the posterior thigh of each individual within the field of view of the ultrasound image, was also tracked using the cross-correlation algorithm. Any movement of the marker was subsequently subtracted from the value obtained for the nerve movement for the same trial.

5.3.5 Reliability

All six healthy subjects participated in this aspect of the study. Three trials during each cervical spine position, for plantar flexion and dorsi-flexion, were conducted on the right limb only. Intra-session reliability of sciatic nerve longitudinal excursion for the slump test for both ankle and cervical spine positions was calculated using Intraclass Correlation Coefficient (ICC$_{3,1}$). Overall, when the cervical spine was maintained in flexion and the ankle dorsi-flexed, the sciatic nerve moved in a distal direction by an average of 0.85mm (Standard Deviation (SD)=0.48mm), whilst upon return of the ankle to a plantar flexed position, the nerve moved a mean 0.6mm (SD=0.36mm) in a proximal direction.
Cervical extension coupled with ankle dorsi-flexed caused distal excursion of the sciatic nerve by 1.08mm (SD=0.1mm). Alternatively, ankle plantar flexion for the same neck position caused proximal movement of the nerve in the posterior thigh (0.35mm; SD 0.36mm). The reliability of the excursion of the nerve in the posterior thigh within the same session, but between trials was on the whole “fair” to “good” (0.68-0.83) (Coppieters et al., 2002) (Table 5.1).

### Table 5.1: Intraclass Correlation Coefficient (ICC$_{3,1}$) of the longitudinal excursion of the sciatic nerve in the posterior thigh during the slump test within the same testing session, in healthy individuals.

<table>
<thead>
<tr>
<th>Cervical spine position and ankle motion during the slump test</th>
<th>(ICC$_{3,1}$)</th>
<th>SEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cervical extension + ankle plantar-flexion</td>
<td>0.68</td>
<td>0.15mm</td>
</tr>
<tr>
<td>Cervical extension + ankle dorsi-flexion</td>
<td>0.73</td>
<td>0.04mm</td>
</tr>
<tr>
<td>Cervical flexion + ankle plantar-flexion</td>
<td>0.74</td>
<td>0.1mm</td>
</tr>
<tr>
<td>Cervical flexion + ankle dorsi-flexion</td>
<td>0.83</td>
<td>0.20mm</td>
</tr>
</tbody>
</table>

"SEM"=standard error of mean

Viewing the findings of Table 5.1, fair to good reliability scores (ICC=0.68-0.83) for all cervical spine and ankle positions, were obtained between trials of the modified slump test in this study, in healthy individuals. These results concur with those presented by Ellis et al. (2008) who reported ICC=0.75 for longitudinal excursion of the sciatic nerve in the posterior mid-thigh during a sliding technique.
as the patient was placed in a modified slump position. With sufficient reliability evident in healthy individuals for evaluating sciatic nerve excursion during the slump test, testing subsequently commenced on injured athletes.

5.4 Case studies of longitudinal excursion of the sciatic nerve in posterior thigh injured athletes during the slump test.

All three hamstring injured athletes completed each component of the slump test in this study and no withdrawal requests were made. The probe was located a mean 16.6cm (range 15-18cm) proximal to the popliteal crease in the injured group, indicating that probe placement was relatively standardised for all participants throughout testing. Each of the three injured subjects who participated in this study are subsequently presented, as individual case studies.

5.4.1 Case study 1

The subject was a 24 year old male, semi-professional rugby union player who sustained a posterior thigh injury to the right limb whilst accelerating during a competitive match. The physical assessment conducted by the lead sports rehabilitator at the patient’s club 72 hours, later revealed a decrease in hamstring muscle strength when manually muscle testing the right leg compared to the left. Pain was experienced during passive hip flexion with knee extension maintained, occurring earlier in range in the injured leg compared to its uninjured counterpart.
No bruising or swelling was evident in the posterior thigh at any stage following injury and a non-antalgic gait was reported. The patient had suffered a posterior thigh injury to the same leg six months previously.

Fourteen days following injury onset, the patient presented to the University of Salford human performance laboratory and participated in this study. Examination of the site of pain in the posterior thigh using high frequency ultrasonography revealed no evidence of muscle damage. The longitudinal excursion of the sciatic nerve in the injured leg, during the slump test was then examined in the patient.

During the slump position, irrespective of cervical spine position, when the ankle joint moved into dorsi-flexion, the sciatic nerve in the posterior thigh persistently moved in a distal direction (Figure 5.3). Contrastingly, when the ankle moved into plantar-flexion during the slump test with both cervical spine positions, the sciatic nerve always moved in a proximal direction as denoted by a "-" sign (Figure 5.3).
"CF+DF" = cervical flexion with ankle dorsi-flexion
"CE+DF" = cervical extension with ankle dorsi-flexion
"CF+PF" = cervical flexion with ankle plantar flexion.
"CE+PF" = cervical extension and ankle plantar flexion
"+" = the sciatic nerve moves distally, towards the ankle joint
"-" = the sciatic nerve moves proximally, towards the hip joint

Figure 5.3: Case study 1: The longitudinal excursion (mm) of the sciatic nerve in the posterior thigh during the slump test for varying cervical spine and ankle positions in an athlete with no evidence of hamstring muscle damage on ultrasound imaging.
When the ankle moved into dorsi-flexion during the slump test whilst the cervical spine was maintained in flexion, the sciatic nerve in the posterior thigh moved 0.85mm less in the injured leg (0.37mm) than uninjured limb (1.22mm). When the ankle was moved into plantar flexion for the same neck position however, the nerve moved 0.17mm less in the uninjured limb (-1.69mm) than the pathological one (-1.86mm). Maintaining the cervical spine in extension, the sciatic nerve moved a greater longitudinal distance in the injured limb (1.4mm) compared to the healthy one (1.05mm) during ankle dorsi-flexion. However, when the ankle was moved into plantar flexion during the slump test for the same cervical spine position, the sciatic nerve in the posterior thigh moved less in the injured limb (-0.56mm) than the asymptomatic leg (-1.47mm).

5.4.2 Case study 2

A 24 year old 1500 metre male runner, with a two year history of recurrent left posterior thigh pain, presented to a senior physiotherapist within the English Institute of Sport, complaining of left posterior thigh pain 14 days prior to participation in this study. The patient reported the pain to commence during high speed running. On physical examination, a 15% strength deficit of the hamstring muscles in injured leg, compared to its healthy counterpart, was discovered. Pain at end of range of the straight leg raise test and with knee extension whilst the hip was placed in 90° hip flexion, was recorded. No bruising or swelling in the posterior thigh was evident during assessment and a normal gait was present.
Upon examination of the athlete’s site of pain in the posterior thigh using high frequency ultrasound, no radiographic evidence of any muscle damage was discovered. Investigating the longitudinal excursion of the sciatic nerve in the posterior thigh during the slump test in this subject, displayed the theory of convergence, as the sciatic nerve always moved in a distal direction as the ankle joint moved into dorsi-flexion (Figure 5.4). When the ankle underwent plantar flexion, the sciatic nerve consistently moved towards the hip joint, in a proximal direction, denoted by a "-" sign.
Figure 5.4: Case study 2: The longitudinal excursion (mm) of the sciatic nerve in the posterior thigh during the slump test for varying cervical spine and ankle positions in an athlete with no radiological evidence of hamstring muscle damage.

During the slump test with cervical flexion, when the ankle was moved into dorsi-flexion, the sciatic nerve in the posterior thigh moved 1.58mm less overall in the injured limb (0.75mm) than the uninjured one (2.33mm). Even when the
cervical spine was placed into extension and the same ankle manoeuvre executed, the nerve still moved less (1.08mm) in the pathological limb than the healthy one (1.75mm). As the cervical spine was maintained in flexion and the ankle plantar-flexed, the sciatic nerve still moved less overall in the injured limb (-0.79mm) than asymptomatic leg (-1.42mm). However, when the cervical spine was placed into extension and the same ankle movement conducted, the nerve moved a further distance in the injured leg (-0.37mm) than the uninjured limb (-0.32mm); albeit a minute difference (0.05mm).

5.4.3 Case Study 3

A 20 year old male, semi-professional rugby union player, with no history of posterior thigh pain, sustained a posterior thigh injury 11 days prior to participating in this study. The injury occurred to the left leg whilst sprinting during a competitive match. Upon physical assessment by the sport rehabilitator at the player's club, 72 hours post injury onset, a reduction in isometric strength as measured using manual muscle testing, of the hamstring muscles in the injured limb was evident when compared to the healthy limb. Active knee extension, when the hip joint was placed in 90° hip flexion, caused pain and a reduction in range of motion in the injured limb. No bruising or swelling was evident at any stage following injury onset. The patient reported antalgic gait, in terms of limping and pain when using long strides when walking, up to 72 hours post injury.
Upon examination of the site of pain in the posterior thigh using high frequency ultrasound in the human performance laboratory, evidence of haematoma within the hamstring muscle group was discovered and lying in close proximity to the sciatic nerve (Figure 5.5).

Figure 5.5: Case study 3: Haematoma in the hamstring musculature, indicative of muscle damage, lying in close proximity to the sciatic nerve.
Ankle dorsi-flexion during the slump test caused the sciatic nerve segment examined in the posterior thigh to always move in a distal direction, towards the ankle joint, whilst plantar flexion caused proximal excursion of the nerve; a finding denoted by the "-" value in Figure 5.6.

"CF+DF"=cervical flexion with ankle dorsi-flexion
"CE+DF"=cervical extension with ankle dorsi-flexion
"CF+PF"=cervical flexion with ankle plantar flexion.
"CE+PF"=cervical extension and ankle plantar flexion
"+"=the sciatic nerve moves distally, towards the ankle joint
"-" = the sciatic nerve moves proximally, towards the hip joint
Upon examination of the sciatic nerve during the slump test with varying ankle and cervical spine positions, the nerve moved more when the spine was flexed and the ankle dorsi-flexed in the injured limb (0.65mm) than the uninjured one (0.19mm). This was a finding also discovered when the spine was extended for the same ankle manoeuvre, as the nerve in the injured leg moved 0.43mm more than the nerve segment in the healthy limb (Figure 5.6). When the cervical spine was sustained in flexion and the ankle moved into plantar flexion, again the sciatic nerve moved a greater longitudinal distance in the injured limb (-0.79mm) than its uninjured counterpart (-0.29mm). However, the same was not evident when the spine was extended during ankle plantar flexion, as the nerve in the posterior thigh of the healthy limb moved a greater distance (-0.43mm) than the injured leg (-0.36mm); a difference however, that is minimal (0.07mm).

Taking the average of the magnitude of excursion of the sciatic nerve for specific neck and ankle positions during the slump test, of the three subjects in this study highlight differences in the amount of nerve excursion which occurs with ankle dorsi-flexion and plantar flexion. Viewing the results of Table 5.2 it is
evident that when the cervical spine was maintained in extension during the slump test, the sciatic nerve moved a greater net distance during ankle dorsiflexion than plantar flexion; this difference was not as pronounced however when the cervical spine was flexed.

Table 5.2: Mean longitudinal excursion of the sciatic nerve (mm) in the posterior thigh during the slump test in posterior thigh injured athletes (n=3).

<table>
<thead>
<tr>
<th></th>
<th>Injured cohort</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Injured leg</td>
</tr>
<tr>
<td>Cervical spine extension + ankle plantar-flexion</td>
<td>-0.43mm</td>
</tr>
<tr>
<td>Cervical spine extension + ankle dorsiflexion</td>
<td>+1.21mm</td>
</tr>
<tr>
<td>Cervical spine flexion + ankle plantar-flexion</td>
<td>-0.59mm</td>
</tr>
<tr>
<td>Cervical spine flexion + ankle dorsiflexion</td>
<td>+0.59mm</td>
</tr>
</tbody>
</table>

"+" = denotes the sciatic nerve moving distally, towards the ankle joint

"-" = denotes the sciatic nerve moving proximally, towards the hip joint

During ankle dorsiflexion, the sciatic nerve in the posterior thigh moved on average between 1.17mm and 1.21mm for the three injured athletes for both limbs, whilst when the ankle was returning from this position to plantar-flexion, the same nerve segment only moved between 0.43mm and 0.741mm. During the slump test with cervical flexion, as the ankle moved into dorsiflexion, the sciatic nerve moved between 0.59mm and 1.13mm in all participants; whilst the returning movement to plantar-flexion ranged between 0.59mm and 1.25mm (Table 5.2).
5.5 Discussion

The aim of this study was to investigate sciatic nerve longitudinal excursion in the posterior thigh during the slump test in athletes presenting with posterior thigh pain. A radiological confirmed hamstring strain did not affect longitudinal excursion of the nerve in one individual during the slump test with cervical flexion and ankle dorsi-flexion. Alternately, for the same manoeuvre in the remaining two athletes, both of whom had an absence of muscle damage on scanning, sciatic nerve excursion was reduced. The direction of nerve movement was also examined in this study; the sciatic nerve consistently moved in a distal direction with ankle dorsi-flexion, whilst plantar flexion caused the nerve to move proximally. The latter ankle movement caused less over-all excursion of the nerve than when the ankle was moving into dorsi-flexion.

The concept of convergence whereby a nerve segment moves towards the moving joint in neurodynamic tests (Coppieters et al., 2006a), was evident for the sciatic nerve in the posterior thigh, in all participants of this study during the slump test. When the ankle moved into dorsi-flexion during the slump test, irrespective of cervical spine position, the sciatic nerve always moved in a distal direction towards the moving joint. Previous research has also demonstrated the innate property of peripheral nerves to converge towards a moving joint during neurodynamic tests in animals (Boyd et al., 2005; Babbage et al., 2006) and humans (Coppieters et al., 2003a; Dilley et al., 2003; 2007).
The concept of divergence, where a nerve realigns along the shortening nerve bed by gliding away from the moving joint (Wright et al., 2001) was also demonstrated in this research as, on the return of the ankle joint from dorsiflexion to plantar-flexion during the slump test, the sciatic nerve moved proximally in all three case studies; as if returning to its original position. Peripheral nerves have been shown in research, to elongate with a tensioning manoeuvre (i.e. median nerve and elbow extension) and shorten with the removal of that movement (i.e. median nerve and elbow flexion) (Zoch et al., 1991); the latter causing a reduction in tension within the nerve (Millesi et al., 1990). The magnitude of excursion for the sciatic nerve in this study however, differed between ankle dorsi-flexion and plantar-flexion. When the ankle moved through dorsi-flexion during the slump test with cervical extension greater excursion of the sciatic nerve occurred than when the ankle was plantar flexing, in both limbs. A similar finding was evident during the slump test when the neck was flexed, but not to such a magnitude. These findings possibly occurred due to the visco-elastic properties of peripheral nerves.

Driscoll et al. (2002) discovered a segment of the sciatic nerve in rabbits to cope with increases in strain of 8% and 16%, by dissipating the tension generated, particularly in the first 20 minutes. The authors reported peripheral nerves to cope exceptionally well with gradual increases in elongation due to the stress-relaxation property of nerves, whereby there is a reduction in tension when the nerve is stretched to a fixed point. In this particular study, it is possible that
ankle dorsi-flexion during the slump test caused the sciatic nerve segment to elongate, increasing the strain within the nerve thereby leading to a relaxation response within the nerve. Consequently, the nerve may have been in a relaxed, temporary elongated position prior to ankle plantar flexion being initiated, resulting in the nerve not moving the same magnitude as with dorsi-flexion.

Reduced mobility of the sciatic nerve has been postulated to occur as a consequence of hamstring injury, as the resultant scar tissue from the muscular injury can adhere to the nerve, thereby decreasing the nerve’s ability to move freely (Shacklock, 2005a, Turi and George, 1998). What makes this author sceptical that minor muscle damage can alter the mobility of the sciatic nerve by adhering to it is based on the fact that for the nerve to become tethered within a forming scar tissue, the nerve must lie within or in close proximity to the injured site. The anatomical localisation and tissue involvement of acute hamstring strains is variable and possibly dependant on the mechanism of injury (Askling et al., 2000). Verrall et al. (2003) reported no predominant site for hamstring muscle injury in 83 athletes with clinically diagnosed hamstring strains, as investigated using MRI. When classified as “upper”, “middle” or “lower” hamstring injuries, no trend for the most common site to be injured within the muscle group was discovered by these authors. The likelihood of muscle damage following hamstring injury occurring directly over the sciatic nerve at some point during its course in the posterior thigh is weak. Of the three hamstring-injured athletes who volunteered for this study, only one subject showed evidence of muscle damage
on ultrasound scanning with evidence of a haematoma in close proximity to the sciatic nerve.

Sciatic nerve entrapment by the hamstring muscles has been documented in research by Carmody and Prietto (1995), who discovered the sciatic nerve to be tethered amongst scar tissue which had developed as a consequence of avulsion of a portion of the origin of the hamstring muscles from the ischial tuberosity. The patient in the case study had undergone a traumatic mechanism of injury and presented with lower limb sensory symptoms, foot drop, severe acute denervation of the common peroneal portion of the sciatic nerve and complete denervation of the long head of biceps. Carmody and Prietto (1995) concluded that the haematoma caused by the injury, lead to the formation of scar tissue adjacent to the sciatic nerve, which resulted in the progressive entrapment of the nerve. Significant reductions in longitudinal excursion of the median nerve was reported post-surgery by Erel et al. (2009), in patients who had 100% division of the nerve. Whilst the nerve moved 2.54mm in the uninjured limb, when imaged at the same site in the injured forearm, a significant reduction in median nerve movement was evident (2.15mm; p=0.02). The authors attributed the decreased longitudinal nerve movement to the formation of fibrotic scar tissue at the site of repair, particularly considering the longer the duration between injury onset and repair, the greater the reduction in nerve movement (p=0.001).
In the research presented by Carmody and Prietto (1995) and Erel et al., (2009), a significant injury with substantial nerve damage caused entrapment of a peripheral nerve. The extent of muscle damage reported in Carmody and Prietto's (1995) case study is not that which typically presents in Grade 1 hamstring muscle injuries, as sensory and motor disturbances in the sciatic nerve distribution is not a commonly occurring consequence of minor hamstring strain. Whilst such a blatant entrapment of the sciatic nerve, as seen in Carmody and Prietto's (1995) case study, may not occur as a consequence of minor hamstring injury, there is the potential that minute nerve disturbances may be the resultant effect of muscle strains. Muscle strains can be complicated by the destruction of intramuscular nerve branches, which can leave part or the whole of a muscle denervated (Kaariainen et al., 2000).

Muscle strains, as the result of an excessive tensile force, typically result in overstrain of the myofibers, with subsequent rupture of this structure (Jarvinen et al., 2005). As a consequence of the rupture of the myofibers, a gap between both ends of the myofibers results; this being the area whereby the haematoma and resultant scar develops. In the middle third of the myofiber, lies its neuromuscular junction (NMJ), whereupon, following injury, usually leaves the NMJ on one stump of the injured myofiber, whilst the other stump loses its connection with the NMJ and subsequently becomes denervated (Kaariainen et al., 2000). During the healing process, the denervated stumps are reinnervated by axons sprouting from nerves of the innervated stumps on the other side of the
scar (Rantanen et al., 1995). These axons pierce through the scar tissue and induce formation of a new NMJ on the opposing stump. However, if the scar tissue is too dense, these axonal sprouts may be unable to penetrate through it and the remaining stump may remain denervated, undergo neurogenic atrophy and be replaced by connective tissue (Kaariainen et al., 2000). It is possible that with any muscle strain, that denervation of one of the stumps of the injury site may occur as a consequence of scar tissue formation. Therefore, whilst it might not be entrapment of the sciatic nerve which occurs during hamstring injury, it may be that axonal regeneration is hindered during the healing process due to the formation of the scar tissue, leading to reduced mobility of both the sciatic nerve and injured muscle. However, viewing the findings of Case Study 3, it appears unlikely that nerve entrapment occurs as there was no evidence of reduced mobility during all aspects of the slump test, with cervical extension and plantar flexion being the exception.

Longitudinal excursion of the sciatic nerve in the posterior thigh in the injured limb where evidence of haematoma was discovered, exceeded that of the healthy limb in Case Study 3 during the slump test. During cervical flexion and ankle dorsi-flexion, the sciatic nerve in the injured posterior thigh (0.65mm) moved almost 3.4 times that of the uninjured limb (0.19mm). This particular aspect of the slump test is presumed to cause the greatest strain of all the four manoeuvres conducted in this study on the sciatic nerve, as the nerve tract is elongated with concomitant cervical flexion and ankle dorsi-flexion (Smith, 1956).
Whilst Case Study 3 supports the author of this thesis’ scepticism that actual hamstring muscle damage to the hamstrings can tether the sciatic nerve, a larger sample size would give a much clearer indication as to the actual consequences of haematoma on nerve excursion.

Case studies 1 and 2 had no evidence of muscle damage on ultrasound examination, yet during cervical flexion with dorsi-flexion of the slump test, a manoeuvre which places the most strain on the sciatic nerve, less longitudinal excursion of the sciatic nerve was discovered in the injured limb (case study 1=0.37mm; case study 2=0.75mm) than uninjured limb (case study 1=1.22mm; case study 2=2.33mm). Case study 2, who had a two year history of posterior thigh injury to the same limb, actually had decreased longitudinal nerve excursion of the sciatic nerve during the slump test for all manoeuvres of the test, with cervical extension and plantar flexion being the exception. Little difference existed between limbs for cervical extension and ankle plantar flexion (0.05mm), possibly due to the nerve being placed under little strain as the nerve tract was relatively unloaded. Case study 1, who reported a history of posterior thigh pain six months prior to the current injury, also had no evidence of muscle damage on imaging, yet had reduced longitudinal excursion of the sciatic nerve in the injured posterior thigh during the slump test with cervical flexion and ankle dorsi-flexion (0.37mm), compared to the healthy limb (1.22mm). However, variability in results occurred during the remaining positions used in the slump test, with reduced excursion also being evident during cervical extension and plantar flexion in the
injured leg (0.56mm) than uninjured limb (1.47mm). The remaining two positions of the slump test used in this study actually showed greater longitudinal excursion of the sciatic nerve in the injured leg compared to its uninjured counterpart in Case Study 1. Nonetheless, despite varying results, the two athletes in this study who had no muscle damage on radiological imaging actually had decreased longitudinal excursion of the sciatic nerve in the injured posterior thigh during the slump test with cervical flexion and ankle dorsi-flexion compared to the asymptomatic leg.

Despite limited numbers, the trend which has emerged from this study is that reduced excursion of the sciatic nerve in the posterior thigh is unlikely in athletes with a radiological confirmed hamstring injury. Injured athletes with significant bruising or swelling could present entirely different and it is possible that with a more severe injury, the mobility of the sciatic nerve may be adversely affected. Interestingly, it was in the athletes with no evidence of muscle damage in the posterior thigh that actually had reduced nerve excursion during the slump test with cervical flexion and ankle dorsi-flexion; a position which places the sciatic nerve under significant strain and therefore assess its sensitivity to elongation (Inman and Saunders, 1942, Smith, 1956). Both of these athletes also had a history of posterior thigh pain and whilst it is unknown whether an actual muscle strain occurred in the previous injury, it appears that reduced nerve movement during the cervical flexion and ankle dorsi-flexion component of the slump test is to be considered in athletes with a history of posterior thigh pain.
5.6 Limitations

Difficulty arose in obtaining participants for this study; particularly those with current hamstring strains. Six participants initially showed willingness to participate in the study, however, due to travel and time restrictions, three of these struggled to attend their allocated time within the testing period. As the aim was to recruit athletes between 10 to 21 days post-injury, this was quite a confined time span in which to organise and co-ordinate testing sessions. Consequently, the sample size of the injured group in this study is limited. Utilising sports people from a variety of sporting disciplines and competitions levels would have increased the sample size of this study.

Despite approaching over 100 sports rehabilitator therapists via their professional organisation, no therapist returned interest in participating in this study. It is possible that therapists may have been unwilling to participate in this study due to feelings that their diagnostic skills were being evaluated. As the hamstring strains were being diagnosed via ultrasound imaging, there may have been clinicians who considered their clinical abilities to be under scrutiny as ultimately their diagnoses were either confirmed or refuted. This is only speculative on the author’s part, but it is a factor worth consideration. Finally, this is the only study of this thesis which had to be conducted in the University laboratory. It is possible that the clubs who participated in previous studies of this thesis regarded the journey too onerous to make, particular those clubs based outside the local area.
No cervical or thoracic spine overpressure was applied to the athletes during the slump test in this study due to an inability to physically apply this manoeuvre. Consequently, it is possible that the sciatic nerve and its expansions were not sufficiently stressed throughout the slump test. Additionally, the knee angle was maintained at 50° throughout testing; again a position which may not place the sciatic nerve under substantial strain. However, as all athletes were considered to be hamstring injured athletes at the time of testing, caution was exercised regarding the magnitude of knee angle which would be used during the testing protocol to minimise any excess stretch being placed on the hamstring muscle group.

5.7 Summary

Clinically-diagnosed hamstring injured athletes did not consistently present with evidence of damage to the muscle group when examined using ultrasonography in this study in general agreement with previous work (Verrall et al., 2001). The presence of hamstring injury did not appear to interfere with the longitudinal excursion of the sciatic nerve in the posterior mid-thigh during the slump test. In those participants presenting with posterior thigh pain in the absent of muscle injury, the origin of the symptoms must arise from structures other than the hamstring muscles. It is feasible that the sciatic nerve or lumbar spine may be the cause of posterior thigh pain in athletes with no radiological evidence of muscle damage; particularly considering the higher incidence of disc
degeneration amongst athletes and in particular those vertebral levels which innervate the hamstrings.

As mentioned throughout this thesis, MRI and ultrasound are not readily accessible tools in semi-professional and amateur sports within the U.K. and therefore clinicians typically rely on clinical tests such as passive intervertebral motion and the slump test to determine whether the lumbar spine or sciatic nerve respectively, contributes to posterior thigh pain. It is currently unknown if low back pain or movement abnormalities within the lumbar spine co-exist with clinically diagnosed hamstring strains. If abnormal intervertebral motion of the spine or lumbar pain is a commonly occurring event in posterior thigh injured athletes, these factors may warrant significant consideration in the diagnostic and treatment process of apparent hamstring strains. Additionally, the location of symptoms or sensations during the slump test may also assist a clinician in determining if the patient has any neural involvement in their complaint of posterior thigh pain.
Chapter 6

Study 4

Location of sensations experienced during the slump test and inter-segmental mobility of the lumbar spine in athletes with a clinically diagnosed hamstring strain.

6.1 Introduction

To differentiate neural and non-neural structures as the origin of a patient’s symptoms who present with posterior thigh pain, therapists use clinical tests such as the slump test. Whilst measurements such as knee angle are advantageous in detecting covert responses during the slump test (Shacklock, 2005a), symptom reproduction is an important measurement to determine neural mechanosensitivity in patients, evident in the findings of the questionnaire presented in chapter two of this thesis (section 2.4, page 95) whereby three-quarters of therapists (78%) cited reproduction of symptoms during the test as indicative of a positive slump test. Obtaining knowledge as to the anatomical location of symptoms experienced during the slump test in a pathological patient can assist therapists during the diagnostic process. For example, an athlete reporting symptoms in the posterior thigh during the cervical flexion component of
the slump, which then dissipate upon execution of cervical extension, indicate a neural cause to the patient’s symptoms. The consequences of such findings may then guide the practitioner to address neural mechanosensitivity to ensure a comprehensive treatment plan is implemented for the posterior thigh injured athlete.

Sensations experienced during the slump test occur predominantly in the distribution of the sciatic nerve, in healthy and symptomatic individuals (Herrington et al., 2010, Kuliart et al., 2005). The buttock and posterior thigh is a common site of sensation production with 50%-57% of sensations being reported in this area during the slump test with cervical flexion (Herrington et al., 2010, Kuliart et al., 2005). The posterior knee is also a common location of symptom production for this same manoeuvre in individuals with ankle inversion sprains (56%) (Pahor and Toppenberg, 1996) and perceived hamstring muscle tightness (66%) (Kuliart et al., 2005). Pahor and Toppenberg (1996) reported the lower leg (uninjured leg 61%; injured leg 64%) to be the primary locations for sensations experienced in patients with ankle inversion sprains during the slump test.

Symptoms experienced during the slump test are not exclusive to the cervical spine being flexed however, as the majority of individuals in Herrington et al’s (2010) study reported sensations in the posterior leg (59%) and posterior knee (56%) with cervical extension. Despite methodological differences, the aforementioned studies reported sensations to occur in the sensory distribution of the sciatic nerve and its branches during the slump test.
Interestingly, during the slump test with cervical flexion, both Kuliart et al. (2005) and Herrington et al. (2010) discovered patients to report symptoms in the lumbar spine area (12% and 19% respectively); the latter author additionally citing 1% of the 92 individuals examined to report symptoms in the lower back with cervical extension, a finding indicating that non-neural structures are the origin of lumbar symptoms in these patients. Low back pain has been previously reported in athletes with hamstring injury (Bennell et al., 1998); however whether this is a result of an actual lumbar spine pathology or neural mechanosensitivity, is unknown.

Abnormal intervertebral mobility is present in patients with low back pain and current hamstring injury (Hoskins and Pollard, 2005, Kulig et al., 2007). Hypermobility within the lumbar spine, particularly at L4/5 and L5/S1 was evident in patients with central non-specific low back pain, when assessed using a posterior anterior manual therapy technique (Kulig et al., 2007). This hypermobility was regarded by the authors to occur as a consequence of disc degeneration, despite not actually investigating disc degeneration within the population. Restrictions in mid thoracic and lumbar spine movement as assessed using inter-segmental motion testing was discovered by Hoskins and Pollard (2005) in one athlete with current hamstring symptoms. The authors however neglected to provide a definition of restriction and omitted details as to the levels of the lumbar spine considered to be restricted. Considering L5/S1 is the most prone lumbar spinal level to disc degeneration in athletes (Ong et al., 2003),
there is the possibility that athletes susceptible to hamstring injury may have underlying altered movement of the lumbar vertebrae; particularly at those levels which innervate the hamstring muscle group as the more caudal the vertebral level the greater the degree of disc degeneration (Ong et al., 2003). If abnormal motion can be demonstrated in a hamstring injured population, this should encourage clinicians to assess the lumbar spine in athletes with posterior thigh injury.

Whilst MRI scans provide in-depth detail as to the extent of degeneration of vertebral discs, this is realistically not the initial assessment tool chosen by clinicians when a patient presents with low back pain, probably due to cost and availability issues. Consequently, therapists rely on manual therapy techniques to identify abnormalities within the spine and use the slump test to indicate any neural involvement with patient symptoms. Abnormal mobility of spinal vertebrae is clinically assessed as gross or segmental motion, the latter technique examining the movement between two adjacent vertebrae (Landel et al., 2008). Therapists typically measure intersegmental movement using spinal accessory motions, such as a central Posterior Anterior (PA) technique, often categorising the movement of the vertebra as experienced by the clinician as hypermobile, normal or hypomobile (Binkley et al., 1995). This manual technique not only allows clinicians to detect abnormal motion within the spinal vertebrae, but also to identify the level of the spine requiring mobilisation or manipulation (Haneline et al., 2008).
The slump test enables clinicians to establish whether the symptoms experienced by a patient are neural or non-neural in origin. Should structural differentiation, via cervical spine extension, have no effect on the presence of low back pain in athletes complaining of posterior thigh pain, there lies the possibility that the lumbar pain and posterior thigh injury are isolated injuries, independent of each other. Conversely, should cervical extension during the slump test eradicate the symptoms of the lumbar spine, there is the possibility that the posterior thigh and low back symptoms are interlinked. This study presents the location of symptoms for both cervical spine components of the slump test in rugby union players with a current clinically diagnosed hamstring strain, in addition to presenting the incidence of abnormal intervertebral mobility of the lumbar spine during a central PA accessory motion technique.

6.2 Aim

The aim of this study was two-fold; firstly to investigate the presence of abnormal intersegmental mobility of the lumbar spine in athletes with current, clinically diagnosed hamstring injury and to establish if abnormalities detected by the examiner correlates to the athlete’s subjective reporting of low back pain since injury onset. Secondly the location of sensations experienced during the slump test in this same population was also investigated in this population, in both the injured and uninjured limbs.
Prior to utilising the central posterior-anterior accessory technique on injured athletes, a study was undertaken on healthy individuals to assess the reliability of using this clinical tool to determine vertebral mobility as previous research has reported clinicians’ interpretation of intersegmental spinal mobility to be poor over-all (Binkley et al., 1995, Hicks et al., 2003, Smedmark et al., 2000). Despite these published findings however, clinicians hold the central PA technique in high regard, considering it to be an accurate technique in assessing intervertebral joint movement (Abbott et al., 2009). The inter-session reliability of the author of this thesis at identifying lumbar vertebrae mobility, as determined using central PA accessory motion, was investigated using a population of healthy individuals prior to conducting any research on injured athletes. The inter-therapist reliability of using this technique was also assessed in the following sub-study.
6.3 The inter-tester and intra-tester reliability of central posterior anterior accessory motion of the lumbar spine in determining segmental mobility and vertebral level of the spine.

6.3.1 Method

6.3.1.1 Participants

A total of ten subjects (5 male, 5 female), mean age 20.9±1.6 years (range 20-25 years) volunteered to participate in this study. The inclusion criteria for individuals were that they were in good health, asymptomatic of any injury or illness. All subjects reported no spinal symptoms, referred symptoms or neuromuscular complaints prior to testing. Individuals possessing a current injury or illness were excluded from participating in this study. Those with a history of spinal surgery, spinal or neural injury, were also omitted from this study. Subjects with abnormal tendon reflexes, myotomal weakness, other complaints or injuries were also excluded. Where manual therapy techniques were contraindicated, these subjects were omitted, as were those in whom central PA testing may be contraindicated (Maher and Adams, 1994). The University of Salford provided ethical approval (Appendix B) for the undertaking of this study. All participants provided informed written consent (Appendix H) prior to participation.
6.3.1.2 Testing Protocol

Two clinicians who complete one full lumbar spine assessment a week evaluated the PA motion of the lumbar spine. The researcher of this study (Therapist A) had five years clinical experience in a musculoskeletal setting, whilst the second therapist (Therapist B) had fifteen years. A central PA consists of applying a central pressure, in a posterior-anterior direction, to the spinous process, whilst the patient lies in a prone position (Landel et al., 2008) and is an integral part of the routine for lumbar spine palpation (Maitland, 2005).

A central PA was conducted on the spinous processes of L1 to L5 inclusive, on all participants by each clinician. The therapist recorded the motion of each spinal level and making a subsequent judgement as to whether the segment was hypermobile (increased movement), normal or hypomobile (increased stiffness) (Appendix I). Therapists were also asked to document on the record sheet, whether the subject experienced any discomfort at each spinal level palpated during the PA motion. Finally, one spinal level was marked arbitrarily on each subject by an independent clinician to determine the therapists’ level of agreement on that specific spinal level. Each therapist identified and assessed the mobility of that marked spinal level.

Each subject was randomly assigned a number for the purpose of this study. Subjects were positioned prone on a plinth, in a concealed cubicle and draped with a blanket to conceal their identity. Only the lumbar spine was
exposed for the therapist to evaluate. The patient’s number was visible within the assessment area so the therapists were aware which subject they are assessing. Each therapist had five minutes to assess and document the mobility of the spinal segments for each patient. Upon completion of the assessment the clinician was instructed to wait outside the cubicle until the other therapist completed their exam before proceeding to the next subject according to the order in which they were allocated to test the subjects. Therapists were not permitted to discuss the findings of their assessments with each other.

To assess the inter-session reliability of each therapist, the entire testing session was conducted 24 hours following the initial testing session. Testing order for each therapist was randomised yet again and the method of testing was exactly the same as initial test.

6.3.1.3 Data Analysis

Percentage of Exact Agreement (PEA) was used to determine the level of agreement between therapists for identification of the specific spinal level (Binkley et al., 1995, Smedmark et al., 2000) in addition to determining the agreement level within and between therapists as to the mobility of the spinal vertebrae.
The PEA was calculated using the following formula (Maher and Adams, 1994):

\[
\text{Percentage of Exact Agreement (PEA) } (\%) = \frac{\text{Number of agreed scores}}{\text{Number of agreed scores} + \text{Number of disagreed scores}} \times 100
\]

A Kappa coefficient for inter-tester and intra-therapist reliability when determining the mobility of the spine was undertaken to determine the level of agreements beyond that expected by chance (Binkley et al., 1995, Smedmark et al., 2000, Hicks et al., 2003). All statistics were calculated using SPSS (version 16).

6.3.2 Reliability Results

All ten subjects completed the testing protocol on both days, reporting no adverse physical effects post-testing as a consequence of the PA technique. The overall percentage level of agreement (PEA) for assessing the mobility of the lumbar spine was 71% between therapists. The PEA for the intra-therapist reliability between sessions for mobility rating, ranged from 67% to 70% (Therapist 1 and Therapist 2 respectively) (Table 6.1).
Table 6.1: Intra-therapist percentage of exact agreement (PEA) and kappa coefficient for determining vertebral segment mobility.

<table>
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<tr>
<th></th>
<th>Therapist A</th>
<th>Therapist B</th>
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<tr>
<td>PEA</td>
<td>67%</td>
<td>70%</td>
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<tr>
<td>Kappa coefficient</td>
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<td>0.397</td>
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*unable to calculate Kappa statistic due to an asymmetrical cross-tabulation table.

Despite relatively good PEA values, the corresponding kappa coefficient for Therapist B was $\kappa=0.397$; a value deemed of “fair” reliability (Landis and Koch, 1977). A kappa coefficient was unable to be calculated for Therapist A, due to the cross-tabulation table being asymmetrical as Therapist A in the initial testing session did not deem any of the lumbar vertebrae to be hypermobile. Therapist B had slightly higher PEA between sessions at determining spinal mobility (70%) than Therapist A (67%).

Evaluating the inter-therapist agreement for determining vertebral segmental mobility between Therapist A and B in this study, resulted in a moderate level of agreement between the clinicians ($\kappa=0.431$) with a PEA of 71%. The kappa coefficient in this study exceeds the majority of the results presented in previous literature whereby inter-therapist reliability ranged from $\kappa=-0.2$ to $\kappa=0.55$ with PEA values of 52%-69% (Binkley et al., 1995, Smedmark et al., 2000, Hicks et al., 2003). Overall, higher inter-therapist reliability at assessing the mobility of the lumbar vertebrae was evident in this study compared to
previous research (Binkley et al., 1995, Hicks et al., 2003, Smedmark et al., 2000), despite the author of this thesis only having five years post graduate experience using this manual therapy technique. It is possible this occurred due to standardisation of how to conduct the actual technique; both clinicians were instructed to use the pisiform of the hand, as opposed to the thumb. The difficulty in achieving excellent reliability between two examiners is that a common definition of normal must exist from which the examiner can determine what is then abnormal; a feat which is problematic as no two examiners have the same experience. Ultimately it lies within the therapist as to their own specific interpretation of spinal mobility.

A final undertaking of this reliability study was to determine the intertherapist reliability in determining a specific level of one of the lumbar vertebrae. This study demonstrated a higher level of agreement between therapists in determining the level of the spine marked than Binkley et al. (1995) (κ=0.30), evident in a kappa coefficient (κ=0.57). The PEA for determining the level of the marked spinal level between the clinicians in this study was 70%. It is possible the reliability of determining spinal vertebral mobility suffered as consequence of the therapists disagreeing on the level of the marked vertebrae. If disagreements exist as to the level of the spine being assessed, when determining the mobility of each vertebra in the lumbar spine, Therapist A could classify what he considers to be L2 as “hypomobile”, whilst Therapist B could regard the same vertebrae to also be hypomobile, and ascertain the level to be L3 as opposed to
L2. As a consequence, reliability between therapists and within therapists is going to be poor if the examiners cannot reliably detect the level in which they are assessing.

It appears that despite varying results as to the reliability of accessory motion techniques (Maher and Adams, 1994; Binkley et al., 1995; Smedmark et al., 2000; Hicks et al., 2003), in particular the ability of therapists to agree on a vertebral level to be examined (Binkley et al., 1995), this manual therapy technique is nonetheless held in quite high regard amongst therapists (Abbott et al., 2009). Abbott et al. (2009) discovered the majority of physical therapists in their study (65.9%; total participants=436) to regard the central posterior-anterior intervertebral motion (PAIVM) as being “somewhat accurate” or “very accurate” for estimating the quantity of movement at a lumbar level; i.e. whether the movement is normal, hypomobile or hypermobile. The majority (>95% cohort) reported that they selected different treatment options for patients with low back pain, partly based on the findings of the lumbar segmental motions. Overall, few physical therapists in Abbott et al’s (2009) study actually showed any scepticism regarding the PAIVM technique. It is possible, based on Abbott et al’s (2009) findings, that practising clinicians are unaware of the equivocal evidence on the reliability of accessory manual therapy techniques and hold them in higher regard than they perhaps deserve. The overall findings of this reliability study display the central PA technique used in this study to exceed that of previous literature. The central PA accessory motion technique was therefore deemed appropriately
reliable to evaluate the mobility of the lumbar vertebrae in hamstring injured athletes.

The subsequent sections of this chapter focus on the aim of this study, whereby the sensations experienced during the slump test and the intersegmental mobility of the lumbar spine in a cohort of athletes with a clinically diagnosed hamstring strain are presented.
6.4 Location of sensations experienced during the slump test and inter-segmental mobility of the lumbar spine in athletes with a clinically diagnosed hamstring strain.

6.4.1 Method

6.4.1.1 Participants

Athletes with current hamstring injuries as diagnosed by their respective medical teams were recruited for this study. Letters of approach were distributed to the senior physiotherapists and sports rehabilitators in professional and semi-professional rugby union and football clubs within the U.K., following which, those clubs interested in partaking received participant information sheets. Those players who then sustained a hamstring injury, as diagnosed by their respective physiotherapists and club doctor, were then approached by their respective therapist as to their willingness to participate; during which time the participant information sheet was issued. Ethical approval for this study was acquired from the University of Salford (Appendix B) prior to any contact with the clubs and written consent was obtained from all participants (Appendix H) subsequent to reading the participant information sheet (Appendix H).
A total of 10 semi-professional (n=7) and professional (n=3) rugby union players\(^4\) (mean age 24.9±3.3 years (range 20-31 years)) with a clinically diagnosed hamstring strain, participated in this study. The current hamstring strain was diagnosed by each player's respective club physiotherapist and team doctor and the average length of time from injury occurrence to testing was 19.8±6.3 days. Information pertaining to the presence of low back pain before injury occurrence and since injury onset to time of testing was also recorded.

6.4.1.2 Testing Procedure

To evaluate the sensations experienced during the slump test each individual was required to mark on a body chart the location of their symptoms since sustaining the hamstring injury, prior to any testing commencing (Appendix J). A body chart was selected due to its ease of use (Petty and Moore, 1998), and it has been used previously as a tool to record the area of sensation (Pahor and Toppenburg, 1996, Yeung et al., 1997).

Intersegmental mobility of the lumbar spine was assessed prior to the slump test in all individuals. The testing procedure undertaken to examine the intersegmental mobility of the lumbar spine in all athletes is similar to that of the reliability study of this chapter (section 6.3, page 221), the primary difference being that the lumbar spine palpated on one occasion only, and no spinal level was marked on the athletes. The author of this thesis was the assessor of the

\(^4\) Caldy RUFC, Doncaster RUFC, Sedgley Park RUFC
lumbar spine, and sequentially palpated from L1 to L5 inclusive, using central posterior anterior (PA) intervertebral accessory motion, categorizing the motion of each vertebra as being normal, hypomobile or hypermobile.

The slump test required the subject to sit on a plinth with thighs fully supported, knees together and the popliteal fossa against the edge of the table. Maintaining the sacrum in a vertical position, the subject allowed the trunk to sag towards the hips thereby ensuring thoraco-lumbar flexion. The cervical spine was initially held in a neutral, comfortable position. A strap was then placed across the shoulders below C7 vertebra, to ensure constant overpressure of thoraco-lumbar flexion. The subject was then requested to bring the chin to chest (i.e. cervical flexion). The examiner applied overpressure to the thoraco-cervical spine during cervical flexion. In this position, the examiner then applied maximum dorsiflexion to the ankle before extending the knee to the point of terminal knee extension. Once in the completed slump position, the subject cited the location of symptoms they experienced at that point and these were marked by an assistant onto a body chart (Appendix J). Subsequent to this, the participant then looked towards the ceiling (cervical extension) and again, cited the area of sensations experienced during the slump test. Any sensations from the handholds utilised during testing were discounted from the results.

Three trials were conducted for both cervical flexion and extension positions of the slump test on both limbs in each athlete. Whilst the testing
sequence of the chosen leg to be tested was randomised, each trial commenced with cervical flexion.

6.4.1.3 Data Analysis

The interpretation of the mobility of the lumbar spine by the examiner was classified as normal, hypermobile or hypomobile; the latter two terms being categorized as abnormal motion of the vertebral segment. The citation of low back pain during hamstring injury by the athlete was categorized for analysis purposes as simply being “present” or “absent”. The data for this particular study is all categorical in nature, thereby resulting in a Phi-coefficient statistical analysis being utilized to establish the strength of association between these variables (Coolidge, 2006).

Whilst a chi-square test measures the existence of an association (Kinnear and Gray, 2000) a phi coefficient actually measures the strength of association between two dichotomous variables; the values of the latter statistical test, ranging from -1.0 to +1.0 (Coolidge, 2006). The strength of association between abnormalities detected by the examiner during PA accessory motion at L4 and L5 and the patient’s reporting of low back pain since injury onset was investigated. The location of sensations experienced during testing, as marked on the body charts, was assigned to a category number related to a specific area of the body (Figure 6.1). The total number of patients who marked that specific area was then calculated.
6.4.2 Results

Of the ten rugby union players who participated in this study, seven participants recalled experiencing lower back pain (i.e. lumbar pain) before the hamstring injury occurred, with six of these players reporting non-resolution of these symptoms from injury onset to time of testing. One player reported no low back pain prior to onset of injury, but experienced symptoms following hamstring injury occurrence.

A greater number of abnormalities in motion existed during the central posterior anterior (PA) technique of the lumbar spine in the more caudal...
vertebrae (L4/L5) when compared to the more proximal levels (L1/L2) (Figure 6.2). L1 had no abnormalities in motion detected by the examiner; however, the more caudal the vertebrae, the fewer incidence of normal motion recorded and the greater the incidence of hypomobility. Hypermobility was only evident at L3, L4 and L5 levels; with very few episodes of this abnormality reported (Figure 6.2).

Figure 6.2: The number of hamstring injured athletes (total=10) who were reported to have normal, hypomobility or hypermobility at each of the lumbar vertebrae, as measured using a central posterior-anterior intervertebral accessory movement.
The examiner cited L4 to be hypomobile in five players of the cohort (50%), whilst hypermobility was regarded as being present in one individual during PA accessory motion. Six players (60%) were deemed by the examiner to have a hypomobile L5 segment, with only one player deemed to be hypermobile at this segment. A total of five players in the entire cohort reported experiencing symptoms at L4 during PA accessory motion of that level, whilst five athletes cited symptoms at L5 during the PA technique.

On examining the strength of association between the examiner perceiving abnormalities at L4 upon PA motion testing and the subjective reporting of LBP since the hamstring injury occurred, a weak positive correlation between the variables ($\phi=0.408; p>0.05$) was discovered (Table 6.2). At L5, little association was discovered between the examiner perceiving abnormalities to exist during the PA technique and the subjects reporting low back pain since injury occurrence ($\phi=0.048; p>0.05$) (Table 6.2).
Table 6.2: The strength of association, as measured using phi-coefficient, between abnormalities detected at L4 and L5 using the posterior-anterior (PA) accessory intervertebral motion technique and the subjective reporting of low back pain by participants since hamstring injury onset.

<table>
<thead>
<tr>
<th>Is there an association between...</th>
<th>Phi-Coefficient value</th>
<th>Significant value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Perceived abnormalities at L4 upon PA motion testing and the subjective reporting of LBP by the athlete since injury onset?</td>
<td>0.408</td>
<td>0.197</td>
</tr>
<tr>
<td>Perceived abnormalities at L5 upon PA motion testing and the subjective reporting of LBP by the athlete since injury onset?</td>
<td>0.048</td>
<td>0.880</td>
</tr>
</tbody>
</table>

"L4"=fourth lumbar spine vertebra

"L5"=fifth lumbar spine vertebra

"PA"=posterior anterior accessory motion

"LBP"=low back pain

The location of symptoms experienced in the hamstring injured cohort in this study, since time of injury, was widespread and not limited to the hamstring region (Figure 6.3). All players (100%, n=10) marked the posterior thigh region as the area where symptoms were experienced as a consequence of their hamstring injury. In addition to this, 40% reported symptoms in the lumbar region, whilst 20% and 10% reported symptoms in the popliteal fossa and thoracic region respectively.
Figure 6.3: The location of symptoms experienced since posterior thigh injury occurrence in professional and semi-professional rugby union players (n=10). These are sensations experienced since time of injury and not during the slump test.

In the injured leg, during the cervical flexion component of the slump test, 9 players (90%) reported sensations in the posterior thigh, with half the cohort (n=5) citing discomfort in the lumbar spine region (Figure 6.4A). Only two players experienced sensations in the popliteal fossa. Cervical extension during the slump test resulted in a reduction in the number of participants who experienced sensations in the posterior thigh (50%), lumbar region (10%) and popliteal fossa (10%) (Figure 6.4B) when compared to when the cervical spine was flexed, in the
injured limb. There was only one player who did not report sensations in the posterior thigh region of the injured leg during any component of the slump test, citing only symptoms in the lumbar spine.

Figure 6.4: Location of symptoms during the slump test with cervical flexion (A) and cervical extension (B) in the injured limb.

Over half the cohort (60%) reported sensations in the posterior thigh of the uninjured leg during the slump test with cervical flexion, with 40% citing lumbar spine symptoms (Figure 6.5A). Only one player reported experiencing sensation in the thoracic region and popliteal surface. Cervical extension in the injured leg
caused 40% of athletes to experience sensations in the posterior thigh, with no symptoms reported elsewhere by all players (Figure 6.5B).

Figure 6.5: Location of symptoms during the slump test with cervical flexion (A) and cervical extension (B) in the uninjured limb.
6.4.3 Discussion

The overall aim of this study was to investigate the presence of intersegmental altered motion in the lumbar spine as measured using a central posterior-anterior accessory motion technique and to present the location of symptoms typically experienced during the slump test in athletes with a clinically diagnosed hamstring strain. Abnormalities of intersegmental motion, particularly hypomobility, occurred more frequently in the more caudal levels of the lumbar spine, such as L4 and L5. Hypermobility was a rare occurrence at any lumbar spinal level in the cohort. No significant association was discovered between movement abnormalities at L4 and L5 and the athletes reporting low back pain since hamstring injury occurrence. Sensations experienced by the participants of this study during both cervical spine components of the slump test were confined to the lumbar, buttock, posterior thigh and popliteal fossa region in the injured and uninjured limbs.

The majority of participants experienced sensations in the buttock and posterior thigh region during the slump test with cervical flexion (60%) in the uninjured limb in this study; a result concurring with previous research (Kuliart et al., 2005, Herrington et al., 2010), whereby 50-57% of participants cited sensations to occur in this region also. When the spine was extended, 40% of participants cited sensations in the buttock and posterior thigh in this study; findings similar to Herrington et al. (2010) who reported 44% of their cohort to experience sensations in this region for the same manoeuvre. When the slump
test was conducted with cervical flexion in the injured limb, a greater number of participants experienced sensations in the posterior buttock and thigh (90%) when compared to the uninjured limb (60%). It is noticeable that the locations of symptoms during the slump test in research and this study occurred primarily in the posterior aspect of the body; areas corresponding to the distribution of the sciatic nerve (Kuilart et al., 2005; Herrington et al., 2010).

Whilst the location of sensations in this study and that of Kuliart et al. (2005) were primarily confined to that of the posterior limb and lumbar spine, Herrington et al. (2010) reported sensations to occur in unexpected locations within the body during the slump test. A minor portion (2%-5%) of the aforementioned author’s cohort reported symptoms in the anterior thigh, knee or dorsum of foot regions area. Considering the slump test is not considered to be the most appropriate neurodynamic test to assess symptoms in the anterior thigh, with the femoral nerve test being advocated as a more suitable choice (Shacklock, 2005a), these are surprising findings by Herrington et al. (2010). However, movement of the upper lumbar nerves (L1 and L2) occurs with trunk and neck flexion (Inman and Saunders, 1942; Brieg and Marions, 1963). Consequently, the slump test can cause movement of these nerve roots, which, should they be sensitive to movement, could inflict symptoms in the anterior thigh and groin during this neurodynamic test.
It appears that the location of the suspected soft tissue injury can influence the location of sensations experienced during neurodynamic testing. Clinically diagnosed hamstring injured athletes in this study experienced sensations primarily in the hamstring area, whilst participants with ankle inversion injuries in Pahor and Toppenberg’s (1996) research, reported symptoms in the lateral lower leg during the slump test with ankle inversion and plantar flexion. However, whilst the aforementioned authors did not ascertain whether these symptoms remained in the lateral aspect of the leg with structural differentiation, this study discovered the position of the cervical spine during the slump test to affect symptom location.

A larger proportion of participants in this study experienced a wider distribution of sensations during the cervical flexion element of the slump test compared to when the cervical spine was extended, particularly in the injured limb. These findings infer that several injured players within this study actually had a “positive” slump test, based on the definition that a positive neurodynamic test is one in which reproduction of patient symptoms or associated symptoms occurs, but which is then relieved by structural differentiation (Nee and Butler, 2006).

A greater number of posterior thigh injured athletes reported sensation in the lumbar spine with the cervical flexion component of the test than its extended position. Half the injured cohort (n=5) of this study cited sensations to occur in
the lumbar spine during the cervical flexion component of the slump test, when conducted on the injured limb, with three of these individuals reporting lumbar spine pain since hamstring injury occurrence. When the slump test with cervical flexion was conducted on the uninjured leg, 40% (n=4) of the entire cohort reported lumbar spine symptoms, with three of these individuals reporting lumbar spine pain occurrence since hamstring onset. Only one individual reported sensation in the lumbar spine when cervical extension was added to the slump test; this participant also had lumbar spine symptoms present since time of injury to the hamstrings.

Over half the cohort (60%; n=6) reported lumbar symptoms prior to (60%) and following (70%) hamstring injury occurrence in this study. A history of back injury has been reported to have a positive correlation with an increased risk of posterior thigh pain, but not with a radiological confirmed hamstring injury (Verrall et al., 2001). The authors suggest that the symptoms experienced in this type of patient are as a consequence of referred pain from neuromeningeal structures as opposed to actual muscle damage. The presence of low back pain in the majority of the injured cohort of this study suggests that in athletes with a current posterior thigh injury, low back pain can co-exist. It is advisable therefore, and in particular having viewed the success of Hoskins and Pollard's (2005) case study, that the lumbar spine should not be omitted in the diagnostic or therapeutic procedures undertaken by clinicians when working with posterior thigh injuries. Further
investigation of low back pain and hamstring injured athletes is warranted on a larger sample size than used in this study.

The central posterior anterior accessory motion of the lumbar spine in the injured cohort of this study exposed intersegmental altered mobility in all the athletes of this study. Whilst these abnormalities (hypermobility or hypomobility) were not discovered at every level of each individual, no one athlete had normal mobility for of the entire lumbar spine. L1 was the only vertebra which had no altered movement on PA assessment by the examiner in the entire cohort, with abnormalities in motion occurring more frequent in the lower vertebrae of the lumbar spine. Hypomobility was the most common abnormal motion of L4 (n=5) and L5 (n=6) whilst hypermobility was evident in one case at each of these spinal levels.

The majority of movement abnormalities detected in the lumbar spine by the examiner during the PA accessory motion technique were of hypomobility, particularly at L4 and L5. Contrastingly, in Kulig et al's (2007) study, hypermobility was more prevalent at the L4/5 and L5/S1 levels in individuals with non-specific low back pain (n=45) when compared to healthy individuals, findings the authors attributed to the presence of early disc degeneration. Intersegmental hypermobility is a predecessor to further disc and joint degeneration of the lumbar spine and subsequent decreased motion of the vertebral segments (Kulig et al., 2007). Whilst the symptomatic cohort utilised in Kulig et al's (2007) study
may have demonstrated early signs of disc degeneration, it is possible that the cohort in this study had surpassed that stage, entering into the phase of hypomobility of the vertebrae of the lumbar spine.

Sports participation is associated with enhanced disc degeneration of the spine (Bono, 2004), evident in athletes as young as 14 years of age (Elliott et al., 1993). If adolescent athletes are displaying degenerative changes of the lumbar spine, the question arises as to the extent of the degenerative changes of the disc and vertebrae for a 25 year old rugby union player; such as those used in this study. With accelerated disc degeneration being evident in athletes (Ong et al., 2003), there lies the possibility that hypermobility of the lumbar vertebrae occurs significantly earlier in sporting individuals than in those individuals who participated in Kulig et al's (2007) study. Consequently, hypomobility may be the more commonly occurring mobility disorder between the lumbar vertebrae in rugby union players, when assessed using central PA accessory motion.

Of those five participants who had a positive slump test in both limbs in this study, all of these participants reported lumbar pain before the posterior thigh injury actually occurred, with four of these athletes reporting no cessation of the low back pain up to the time of testing. Three of these five participants had abnormal motion at the fourth lumbar vertebra (L4) as determined using posterior-anterior (PA) accessory intervertebral motion (hypermobile n=1; hypomobile n=2). At L5 however, four of the five athletes who had a positive
slump test in both limbs, were regarded as having abnormal motion, with hypomobility being evident in all four cases. These findings demonstrate that abnormal intervertebral motion of the lumbar spine, low back pain and neural mechanosensitivity can occur in posterior injured athletes, despite a poor association between lumbar pain and abnormal intervertebral motion evident in this study. However, with such a limited sample size incorporating rugby union players only, these findings cannot be extrapolated to a wider sporting population.

6.4.4 Limitations

Several limitations were identified during this study, particularly the lack of radiological investigatory tools to confirm or refute the presence of hamstring muscle strain within the injured cohort. However, logistically, it was not possible to use either of the radiological investigations due to the testing sessions being conducted at each individual club and whilst a portable ultrasound machine would have been the ideal tool to use, it was not available to the author. Despite the prevalence of low back pain before and during hamstring injury in this study, it is unknown whether the symptoms experienced in the posterior thigh were actually the result of muscle damage to the hamstrings or referred pain from the lower back. One use of MRI in this research, should it have been available, could have been to evaluate the magnitude of disc degeneration within the lumbar
vertebrae of the spine and correlate this to the clinical findings of the therapist using the central PA motions.

The use of mobility rating scales when assessing intersegmental mobility using spinal accessory motion, such as the three-point scale used in this study may be a source of error within themselves (Hicks et al., 2003). The aforementioned authors suggest that the fewer options given to a therapist by which to classify segmental mobility, the greater the reliability error. Contrastingly however, when Maher and Adams (1994) used an eleven point rating scale, the authors reported the majority of clinicians to only use approximately six values within the scale; all in close proximity to each other. This particular study utilised a three-point scale as it was deemed the most representative scale which is used in clinical settings.

The presence of researcher bias when assessing the intersegmental mobility of the spine cannot be eliminated in this study as the researcher was aware of previous findings in research regarding the presence of hypermobility and hypomobility in patients with low back pain and restrictions being associated with hamstring injury. The researcher may therefore have been influenced in determining these abnormal movements in the lumbar spine of the cohort as it was expected abnormalities should occur. To overcome this, a clinician with experience in manual therapy and blinded to the injury status of the cohort, could have been utilised in this study to reduce researcher bias.
The low sample size recruited in this study is also of concern as the potential for Type II error to occur is possible. With non-significant results, there lies the possibility that an actual effect may be undetectable due to the participation of only ten subjects. A larger sample size of athletes from various sports and competition levels would inherently increase the population number. Additionally, the inclusion of an age, sport and sex matched control group would allow a comparison to be undertaken to determine if the presence of abnormal intervertebral movement and low back pain is specific to hamstring injured athletes.

6.4.5 Summary

Altered intersegmental mobility was discovered in ten rugby union players with a clinically diagnosed hamstring strain in this study with hypomobility evident in over half the cohort, particularly at L4 and L5. It is possible that with progressively enhanced disc degeneration than that which is seen in sedentary individuals, hypermobility of the lumbar vertebrae occurs earlier in life in athletes, thereby resulting in intersegmental hypomobility occurring significantly earlier also. The consequences of such altered mobility of the lumbar spine, in particular L5 can only be speculative, but it may contribute to injury or re-injury of the hamstring muscles or referred pain into the posterior thigh.
Hypermobility of an intervertebral disc could result in tears of the annulus fibrosis, leading to an unstable disc and excess movement between the corresponding vertebrae. Further disc degeneration and subsequent hypomobility at L4/L5 or L5/S1, may then result in a reduction in space for the nerve root to exit the spinal canal, causing nerve root compression and ultimately pain along the sciatic nerve tract in the posterior thigh. From a clinician’s perspective, prehabilitation, such as spinal stabilisation exercises, to minimise the effects of disc degeneration and in particular its consequences on the surrounding anatomical structures, could be undertaken to minimise the risk of hamstring injury or posterior thigh pain occurrence.

Clinicians should not regard an apparent hamstring strain as a localised pathology, and should broaden the diagnostic process to include the lumbar spine and the neural system. When conducting neurodynamic tests on pathological patients, therapists should consider the distribution of sensations experienced by the patient and expect the patient to report symptoms along the distribution of the potentially involved nerve. Structural differentiation is a necessity to enable a complete diagnosis of a pathological patient to ensure neural mechanosensitivity is not overlooked.
Chapter 7

Conclusion of “The Slump test and Posterior Thigh Disorders”

The slump test is used to differentiate neural and non-neural structures as the origin of a patient’s symptoms and has been shown in this thesis to be used by clinicians when assessing and treating numerous disorders. The majority of therapists who partook in the questionnaire issued opted to use the slump test in patients with symptoms corresponding to the distribution of the sciatic nerve. An imbalance existed however in the number of therapists who use the slump test as a diagnostic aid and treatment tool, with more clinicians using it diagnostically; the reasons behind being unknown. Further research is required to establish the reasoning as to why therapist are more prone to use this neurodynamic test as a diagnostic aid, but not as a treatment tool, as sliding and tensioning techniques are proposed as appropriate treatment aids for patients presenting with neural mechanosensitivity (Coppieters and Butler, 2008).

The initial study of this thesis revealed the slump test when evaluated to the point of resistance onset as determined by the examiner, to be ineffective in predicting athletes susceptible to hamstring injury. Whilst cervical flexion had a marginally greater effect on knee angle between limbs in those athletes who had sustained a hamstring injury at follow-up compared to those who did not, this was
non-significant. Based on these findings, it is possible that the slump test is too gross a clinical test to ascertain whether discrete changes in neural sensitivity to movement are present prior to hamstring injury occurrence.

However, interesting findings were discovered during the slump test when conducted on athletes with a current hamstring injury. Biceps femoris activated first of all the remaining variables ($M_{1ST}$, $P_1$ and $R_1$) examined during the slump test in hamstring injured athletes in this thesis; actually having a significantly earlier onset than semitendinosus in the injured limb during cervical flexion. Biceps femoris consistently activated first of all the variables during both cervical spine components of the slump test, irrespective of injury status. This muscle may be activating earlier than the medial hamstring muscle during the slump test with cervical flexion in this study, in anticipation of excess strain being placed on the local neural structures, such as the sciatic nerve. It is therefore possible that biceps femoris acts as a protective mechanism for the neural system in the posterior thigh in the injured cohort of this thesis.

Two athletes in the case studies presented in Chapter 5 (page 193), actually had no muscle damage to the posterior thigh when examined using ultrasound yet presented with decreased longitudinal excursion of the sciatic nerve during the cervical flexion and dorsi-flexion components of the slump test. It is possible that in this type of patient, biceps femoris acts as the primary protector for the nervous system to prevent excess strain being placed on a
nerve with reduced mobility. Based on early cadaveric studies (Inman and Saunders, 1942; Smith, 1956), the sciatic nerve and its expansions are placed under greatest strain during cervical flexion with dorsi-flexion of the slump test; therefore decreased neural mobility for this manoeuvre would indicate a sensitivity of the nerve to elongation. Consequently, in an athlete with posterior thigh pain, but no muscle damage on radiological investigations, biceps femoris may be activating earlier in range of knee extension to prevent excess movement and therefore strain, being placed upon the sciatic nerve.

The slump test, when conducted in athletes with a clinically diagnosed hamstring strain, primarily cause sensations in the distribution of the sciatic nerve, such as the buttock, posterior thigh and lumbar spine. However, the release of cervical flexion during the test subsequently causes a reduction in the number of patients reporting symptoms in these areas, particularly in the lumbar spine. Intersegmental altered mobility of the lumbar spine was evident in all the athletes of this study when assessed using the central posterior anterior accessory motion technique and hypomobility was the most common abnormal motion of the fourth and fifth lumbar vertebrae. Despite these findings however, no statistical relationship was evident between an athlete's subjective reporting of low back pain since injury onset and the intersegmental spinal mobility determined by the examiner. With a limited sample size in this study (n=10), attaining conclusions are difficult as a Type II error is a realistic probability. Larger sample sizes and the use of radiological investigation, such as MRI, to
provide precise information as to the mobility of the lumbar vertebrae in hamstring injured athletes could start to provide a clearer picture of the hypothetical relationship which exists between the lumbar spine and hamstring injury.

The over-all findings of this thesis encourage clinicians to take a broad viewpoint when assessing and treating apparent hamstring injuries. An array of locations of symptom production was evident during the slump test in athletes with a clinically diagnosed hamstring injury, with back pain also being present in several of the cohort examined in this thesis. The mobility of the sciatic nerve should also be considered in the athlete presenting with posterior thigh pain, particularly if an absence of hamstring muscle damage is evident, as differences in longitudinal nerve excursion were discovered to exist between those with and without radiological-confirmed hamstring injury in this thesis. Finally, for therapists working with athletes, who no doubt will be faced with posterior thigh injuries during their career, awareness as to the dominance of biceps femoris following injury is important. Tailoring rehabilitation towards the hamstrings as a generic group may be over-all ineffective due to the asymmetry in onset timing and magnitude of activation between the medial and lateral hamstrings.

Several of the findings of this thesis are novel, as no research to date has investigated whether the hamstring muscles may have this protective mechanism during the slump test, as has been demonstrated in research conducted on the
upper limb (Balster and Jull, 1997, van der Heide et al., 2001). Additionally, the quantification of longitudinal excursion of the sciatic nerve during the slump test in hamstring injured athletes, albeit on a very limited sample size, is also unique and the first of its kind in research. The expansion of the latter study to incorporate a series of case studies would provide a significantly clearer, more definite picture as to the relationship between hamstring injury and sciatic nerve excursion. Future research evaluating not only longitudinal excursion but also transverse movement of the sciatic nerve would be of benefit, particularly as both these movements can occur simultaneous to each other (Ellis et al., 2008) and may be affected under pathological conditions. Additionally, further investigations into the effect sliding and tensioning techniques have on longitudinal excursion of the sciatic nerve in the posterior thigh, particular in athletes with a radiological refuted hamstring injury, would be beneficial. Sliding or tensioning techniques may improve the actual movement of the nerve in the posterior thigh in this type of athlete and is an area which warrants further investigation.
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Appendix A: Slump Test Questionnaire

This questionnaire was developed to determine if and when the Slump test is used in everyday clinical practices amongst physiotherapists, sports rehabilitators etc.

Please take your time to answer all questions if possible. All results are confidential.

<table>
<thead>
<tr>
<th>Qu.</th>
<th>What is your profession?</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>□ Physiotherapist</td>
</tr>
<tr>
<td></td>
<td>□ Sports Rehabilitator</td>
</tr>
<tr>
<td></td>
<td>□ Athletic trainer</td>
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<tr>
<td></td>
<td>□ Biokinetisist</td>
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<td>□ Sports Therapist</td>
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<tr>
<td></td>
<td>□ Chiropractor</td>
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<tr>
<td></td>
<td>□ Other (Please state): __________</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Qu.</th>
<th>Which of the following are you currently employed in?</th>
</tr>
</thead>
<tbody>
<tr>
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<td>□ Private practise</td>
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<tr>
<td></td>
<td>□ Sports Club</td>
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<tr>
<td></td>
<td>□ Hospital</td>
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<tr>
<td></td>
<td>□ GP Practice</td>
</tr>
<tr>
<td></td>
<td>□ Other (please state) Full time/Part-time</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Qu.</th>
<th>Do you use the Neurodynamic test, the Slump for diagnosis purposes?</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>□ Yes If you answered yes, please proceed to Qu. 4</td>
</tr>
<tr>
<td></td>
<td>□ No If you answered &quot;no&quot; please proceed to Qu. 6</td>
</tr>
</tbody>
</table>

Please circle your answer, Yes or No.
Qu. 4  In what patients do you use the slump test as a **diagnosis** tool? Please tick as many as apply.

Patients who present with:

- □ Cervical pain
- □ Thoracic pain
- □ Lumbar pain
- □ Gluteal pain
- □ Posterior thigh pain
- □ Calf pain
- □ Groin pain
- □ Anterior Lower leg pain
- □ Anterior thigh pain
- □ Hamstring strains
- □ Adductor strains
- □ Gastrocnemius/soleus strains
- □ Abnormal reflexes
- □ Dermatomal abnormalities
- □ Myotomal abnormalities
- □ Lower limb radiculopathy
- □ Upper limb radiculopathy
- □ Quadriceps strains
- □ Other

What do you regard as a **positive** slump test? Please tick as many as apply.

- □ When the patient's symptoms are reproduced?
- □ When releasing cervical flexion or ankle dorsi-flexion during the test decreases patient symptoms?
- □ When releasing cervical flexion or ankle dorsi-flexion during the test increases knee extension range?
- □ When there is a difference in symptoms between limbs/sides of body?
- □ When there is a difference in range of knee extension between limbs/sides of body?
- □ When structural differentiation supports a neurogenic source?
- □ Other (please state):

Qu. 6  Do you use the Neurodynamic test, the Slump for **treatment** purposes?

- **Yes**
  - If you answered yes, please proceed to Qu. 7
- **No**
  - If you answered "no" this is the end of your questions.
Qu. 7 In what patients do you use the slump test as a treatment tool? Please tick as many as apply.

Patients who present with:

- □ Cervical pain
- □ Thoracic pain
- □ Lumbar pain
- □ Gluteal pain
- □ Posterior thigh pain
- □ Calf pain
- □ Groin pain
- □ Anterior thigh pain
- □ Lower leg pain (anterior shank)
- □ Lateral calf pain
- □ Plantar surface of foot pain
- □ Dorsum of foot pain
- □ Hamstring strains
- □ Adductor strains
- □ Calf strains
- □ Achilles tendonopathy
- □ Abnormal reflexes
- □ Dermatomal abnormalities
- □ Myotomal abnormalities
- □ Lower limb radiculopathy
- □ Upper limb radiculopathy
- □ Other: (please state)

Thank you for participating in this questionnaire. Should you have any queries, please do not hesitate to contact me.

Regards

Liz Fowler, PhD Candidate, University of Salford; e.m.fowler@pgr.salford.ac.uk
Dr. Lee Herrington, Supervisor, University of Salford; l.c.herrington@salford.ac.uk
## Appendix B: Ethical Approval

<table>
<thead>
<tr>
<th>Title of study</th>
<th>Chapter</th>
<th>Ethical approval code</th>
</tr>
</thead>
<tbody>
<tr>
<td>The slump test in undergraduate education and postgraduate clinical practice.</td>
<td>2 (Study 1)</td>
<td>REP10/044</td>
</tr>
<tr>
<td>Can the slump test be used as a predictive tool for hamstring injury?</td>
<td>3 (Study 2)</td>
<td>RGEC06/3</td>
</tr>
<tr>
<td>Muscle activity, pain and resistance onsets during the slump test in hamstring injured athletes.</td>
<td>4 (Study 3)</td>
<td>RGEC06/116</td>
</tr>
<tr>
<td>The effect of hamstring injury on the longitudinal excursion of the sciatic nerve during the slump test: A preliminary investigation.</td>
<td>5 (Study 4)</td>
<td>RGEC06/116</td>
</tr>
<tr>
<td>Location of sensations experienced during the slump test and inter-segmental mobility of the lumbar spine in athletes with a clinically diagnosed hamstring strain.</td>
<td>6 (Study 5)</td>
<td>RGEC07/120</td>
</tr>
</tbody>
</table>
Appendix C: Study 1: Participant Information and Consent Forms

Can the slump test be used as a predictive tool for hamstring injury?

You are invited to take part in a research study. Before you decide it is important for you to understand why the research is being done and what is involved. Please read the following information carefully and take your time to decide whether or not you wish to take part.

What is the project all about?

Hamstring muscle injuries are extremely common in professional football (11-12% of all injuries) and rugby. Given the high occurrence rate of this injury, identifying the factors which cause hamstring injury is essential, not only to appropriately treat the injury, but also to prevent it reoccurring. Poor hamstring flexibility, muscle strength imbalances, muscle weaknesses, previous hamstring injury and tension in the neural system are believed to be predictive factors in the occurrence of injury in this muscle group. The two areas which are believed to be strongly predictive of hamstring muscle injury occurring are advancing age and previous hamstring muscle injury. Wear and tear (degeneration) of the lumbar spine (lower back) is a factor associated with advancing age. Degeneration of the vertebrae can lead to nerve impingement, which then may lead to a decrease or loss of nerve supply to the hamstring muscles, causing decreased muscle strength of the hamstrings, ultimately leading to injury. Considerable difficulty can exist in distinguishing between minor hamstring muscle strains and injuries involving referred pain from the lumbar spine.

No research to date has evaluated the relationship between the neural response of the sciatic nerve in the back of the thigh and hamstring injury, prior to the injury occurring. The aim of this study is to contribute to an understanding of the role of the sciatic nerve in the occurrence of hamstring muscle strains.

Why have I been chosen?

You have been chosen on the basis that you are a professional or semi-professional football or rugby player, a population considered to be highly susceptible to hamstring injury. You are also regarded to be in good health.

Do I have to take part?

Taking part is entirely voluntary. If you do take part you will be given a consent form to read and sign. You are free to withdraw at any time without giving a reason or prejudice.
What will I have to do?

Testing will be undertaken at a convenient time during training, at your club. It will take up maximum 30 minutes of your time. Prior to testing you will have markings placed on both legs, on the hip, knee and ankle. You will then be tested using the Slump test. You will be asked to sit on a table with the back of your knees against the edge of the bed. You will then be asked to slump your shoulders towards your hips. A strap will be placed over the back of your shoulders and under the bed to hold you in this slumped position. You will then be asked to bring your chin to your chest after which, the examiner will apply some overpressure (via hand) to your head and neck. The examiner will then raise your foot up towards you and subsequently straighten your knee, to a point where the examiner experiences resistance of the limb to the movement. A camera shall record the angle of your knee at this position. You will then be asked to look up towards the ceiling and the examiner will straighten the knee to the point of resistance experienced. Again, the camera shall record your knee angle. Three trials will be taken on each leg for both neck positions. All knee angles will be continuously recorded using video camera.

Following this, your physiotherapist or club doctor shall be contacted at the end of season requesting information as to whether you sustained a hamstring injury during the season.

Is there any risk involved?

The risk involved is minimal as the testing procedure used involves taking you to the point of resistance experienced by the examiner; a measurement which is frequently used clinically during the slump test.

Potential benefits to participants.

By participating in this study you will obtain an assessment of the sensitivity of your sciatic nerve to movement which may (if positive) be used as a technique to decrease your risk of hamstring injuries. This study may also provide an over-all insight into those participants most susceptible to hamstring injury.

Who will see my details and results?

All identities and information obtained during this study will of course remain strictly confidential. The final results of the study will be available to you, and may be published. No players will be identified in any reports generated.

You are free to decide not to be in this trial or drop out at any time.

Please feel free to ask any questions about the nature or demands of the project at any time.
CONSENT FORM

Title of Project: Can the slump test be used as a predictive tool for hamstring injury?

Name of Researcher: Miss Elizabeth Fowler

Please initial box

1. I confirm that I have read and understand the information sheet for the above study.

2. I understand that my participation is voluntary and that I am free to withdraw at any time without my medical care or legal rights being affected

3. I agree to take part in the above study.

Name of patient ___________________________ Date __________ Signature __________

Researcher ___________________________ Date __________ Signature __________

(1 copy for patient, 1 copy for researcher, 1 copy to be filed in notes)
Appendix D: Follow-up Letter for the Slump Test
Predicting Hamstring Injury

Re: Can the slump test be used as a predictive tool for hamstring injury?

Dear

You may recall that in the 2007/2008 pre-season, I undertook some research at 
[CLUB NAME] whereby I examined players at your club, using the passive slump test, 
with the aim of investigating whether the slump test can predict susceptibility to 
hamstring injury. Consequently, this letter is a follow up requesting information relating 
to the players I tested that season; specifically as to whether they sustained a hamstring 

Attached are two documents; one is the names of the players I tested from [CLUB 
NAME], along with the corresponding numbers assigned to them for the purpose of this 
study to ensure player anonymity (see Player Detail sheet). The second document is a 
table, which I kindly request you fill out with details relating to any player who sustained 
a hamstring injury in the time period highlighted above. It is only those who I tested with 
the slump test in the 07/08 pre-season who I am following up, and it is just hamstring 
injuries only I am requesting information on. You are of course not obliged to partake in 
this study and I thank you for your co-operation in my initial testing session. Should you 
be willing to take part in the follow up study, I am asking that you fill out the table of 
results attached and return it to me using the SAE enclosed.

Many thanks for your continuing involvement in my study; it is greatly 
appreciated. Should you have any questions, please do not hesitate to contact me. Best 
wishes for the forthcoming season.

Regards

Elizabeth Fowler BSc. (Hons) GSR
PhD candidate, Directorate of Sport, University of Salford, Salford, M6 6PU.
E.M.fowler@salford.ac.uk; Ph: 0161-2957045 (W)/Mob: 07828916162
Supervisor: Mr. Lee Herrington
L.C.Herrington@salford.ac.uk; Ph: 0161-2952326
Follow-up Questionnaire for the slump test predicting hamstring injur

Please fill out the details of the table below as accurately as possible. The first line is an example of how to

<table>
<thead>
<tr>
<th>Player initials</th>
<th>Did player sustain hamstring injury in the 2007/2008 season?</th>
<th>Which limb sustained the injury?</th>
<th>Date of hamstring injury</th>
<th>What action was the player doing when he injured the hamstring?</th>
<th>No. of weeks or days absent from play</th>
<th>Did the athlete have decreased strength on manual muscle testing of the hamstrings?</th>
<th>Did the athlete have decreased RoM as measured during the straight leg raise?</th>
<th>Did the player have PC on palpation in the posterir thigh?</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC</td>
<td>Yes</td>
<td>Right</td>
<td>12/12/2007</td>
<td>Sprinting</td>
<td>4 weeks</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>
PARTICIPATION INFORMATION SHEET

Muscle activity, pain and resistance onsets during the slump test in hamstring injured athletes.

You are invited to take part in a research study. Before you decide it is important for you to understand why the research is being done and what is involved. Please read the following information carefully and take your time to decide whether or not you wish to take part.

What is the project all about?
When the body moves, nerves continuously move with the body. The fluidness of this movement is often dependant on the structures the nerve passes through; such as muscle and ligaments. The hamstrings are one such structure which has been reported to limit movement of the sciatic nerve. Upon recovery from an injury, the scar tissue forming within the hamstrings can tether the sciatic nerve and compromise its movement through the muscle. This in turn has been reported to be a potential cause of hamstring injury recurrence. The movement of the sciatic nerve is commonly assessed by health professionals using the “Slump” test. Difficulty exists in distinguishing between Grade 1 or minor hamstring muscle strains and injuries involving referred pain. One study found that 57% of players with recurrent hamstring problems had a positive “Slump” test and concluded that tension of the neural structures in the body, can be a cause of recurrent hamstring strains. However, other authors state that it is impossible to know exactly what structures (e.g. nerve, fascia, muscle) is causing pain or reproducing symptoms during the slump test. It has been suggested that determining the onset of muscle activity of the hamstrings during the slump test can be a more reliable method of determining whether the nerve is responsible for symptoms experienced during the slump test. As a result, the aim of this investigation is to examine the muscle activity of the hamstrings during the slump test, and see if they are related to the symptoms experienced during this test.

Why have I been chosen?
You have been chosen on the basis that you are a professional or semi-professional athlete who has sustained a hamstring injury in the past 21 days.

Do I have to take part?
Taking part is entirely voluntary. If you do take part you will be given a consent form to read and sign. You are free to withdraw at any time without giving a reason or prejudice.
What will I have to do?
Testing will be undertaken at a convenient time at your club. You will be tested using a simple test called the “slump” test, whilst an EMG recorder will detect any muscle activity from your hamstrings. Both legs will be tested-the injured and non-injured ones.

Firstly, you will be asked to lie on your front on a treatment bed. To confirm where the EMG electrodes will be placed, the tester will ask you to pull your heel towards your bum and the muscle is palpated (i.e. felt). This will be repeated twice on each leg. You will then have four small areas at the back of your thigh (1cm diameter each), approximately half way down, washed with soap and water, and shaved with a disposable razor. The outside of each knee will also be cleaned in the above manner. Following this, the shaved areas will be cleaned with an exfoliating gel and further cleaned with an alcohol wipe. You will then have 4 self-adhesive electrodes attached to the shaved areas on the back of your thigh, and one placed on the side of your knee and these shall be connected to the muscle activity recording equipment.

You will then be seated on a table, with the back of your knees against the edge of the table. Following this, the slump test will be conducted. During all the testing of the slump test, a video camera will be recording the entire event. You will be asked to slump your shoulders towards your hips. A strap will be placed over the back of your shoulders and under the table to hold you in this slumped position. You will then be asked to bring your chin to your chest after which, the examiner will apply some overpressure (using the hand) to your head and neck. The examiner will then raise your foot up towards you and subsequently straighten your knee. The examiner will only take the knee to a point where the examiner feels resistance within the limb. Also, a push-button device will be given to you and you will be requested to push the button to indicate the moment you feel any pain or symptoms in your body as the knee is being straightened. You are to go to a point where it is mild symptoms which you are willing to tolerate considering the test will be repeated six times in total on each leg. Three trials will be conducted with your chin to chest and also when you neck is extended (i.e. you look at the ceiling). This will then be repeated on the opposite leg. Cameras will be set up at either side of the testing area to record the range of motion achieved at the knee during the slump test.

Is there any risk involved?
The risk involved is minimal as the slump test is a treatment strategy frequently used in the treatment of hamstring strains. As you are going to the point where the examiner feels resistance, and not to the maximum point of knee extension, there is minimal risk involved.

Potential benefits to participants.
By participating in this study you will obtain an assessment of the neural status of your sciatic nerve, during the slump test.
**Who will see my details and results?**

All identities and information obtained during this study will of course remain strictly confidential. The final results of the study will be available to you, and may be published. No participant will be identified in any reports generated.

You are free to decide not to be in this trial or drop out at any time.

Please feel free to ask any questions about the nature or demands of the project at any time.

Researcher’s name: Elizabeth Fowler  
Email: e.m.fowler@pgr.salford.ac.uk

Supervisor: Mr. Lee Herrington  
Email: l.c.herrington@salford.ac.uk
CONSENT FORM

Title of Project: Muscle activity, pain and resistance onsets during the slump test in hamstring injured athletes.

Name of Researcher: Miss Elizabeth Fowler

Please initial box

1. I confirm that I have read and understand the information sheet for the above study.

2. I understand that my participation is voluntary and that I am free to withdraw at any time without my medical care or legal rights being affected.

3. I agree to take part in the above study.

Name of patient __________________________ Date ___________ Signature ______________

Researcher ______________________________ Date ___________ Signature ______________

(1 copy for patient, 1 copy for researcher, 1 copy to be filed in notes)
Appendix F:

Testpoint programme to determine onset of muscle activity, pain and resistance during the slump test.
Details of GUI in Testpoint for EMG analysis

- **Biceps Femoris R**
- **Semitendinosus R**
- **P1 trigger**
- **R1 trigger**

**File open**

- **File**
- **RMS Fitter**

**E=3<2**

**IL**

To find EMG on time - select channel, select section of EMG to analyse, press on time button.

- **channel select**
- **baseline start**
- **Baseline start**
- **start**
- **stop**

**on time**
Details of programmed objects used in Testpo programme

- Biceps Femoris R
- Semitendinosus R
- P1 trigger
- R1 trigger
- File open
- RMS Filter
- calculated time
- Biceps Fem R
- Semitendinosus R
- P1 trig
- R1 trig
- trig1 R1 invert
- trigP1 invert
- data in
- filter1
- filter2
- filter3
- filter4
- filter channel 0
- filter channel 1
- filter channel 2
- filter channel 3
- filter channel 4
- on time analysis
- channel select
- start
- stop
- channel selection
- on time
- filtered data
- Label2
- baseline start
- Baseline stop
- on time
- all chans

- baseline data
- on threshold
- EMG on data set
- wavedata
- zero cross
- convert to sign
- zepoint
- maxindex
- on time
- EMG result plot
- clear and plot 1
- clear and plot 2
- clear and plot 3
- clear and plot 4
- threshold vector for plot
- time for emg plot
Details of programming to open and plot

1) Clear filtered data
2) Clear all channels
3) Clear data in
4) Clear graph Biceps Femoris R
5) Clear graph Semitendonosis R
6) Clear graph P1 trigger
7) Clear graph R1 trigger
8) Set Biceps Femoris R(X vs Y) to 1
9) Set Semitendonosis R(X vs Y) to 1
10) Open File open
11) Input from File open data in up to 1000000000000 "bytes", stopping at
12) Store in data in from File open data in
13) Calculate Biceps Fem R with a=data in
14) Calculate calculated time with a=Biceps Fem R
15) Calculate Semitendonosis R with a=data in
16) Calculate P1 trig with a=data in
17) Calculate R1 trig with a=data in
18) Calculate trigP1 invert with a=P1 trig
19) Calculate trigR1 invert with a=R1 trig
20) Draw graph Biceps Femoris R with calculated time, Biceps Fem R.
21) Draw graph Semitendonosis R with calculated time, Semitendonosis R.
22) Draw graph P1 trigger with calculated time, trigP1 invert.
23) Draw graph R1 trigger with calculated time, trigR1 invert.
Details of programming to allow filtering of data

1) Calculate filter channel 0 with a = data in
2) Calculate filter channel 1 with a = data in
3) Calculate filter channel 2 with a = data in
4) Calculate filter channel 3 with a = data in
5) Calculate filter channel 4 with a = data in
6) Calculate filter 1 with a = filter channel 1 b = RMS Filter
7) Calculate filter 2 with a = filter channel 2 b = RMS Filter
8) Calculate filter 3 with a = filter channel 3 b = RMS Filter
9) Calculate filter 4 with a = filter channel 4 b = RMS Filter
10) Clear graph Biceps Femoris R
11) Clear graph Semitendonosis R
12) Clear graph P1 trigger
13) Clear graph R1 trigger
14) Draw graph Biceps Femoris R with calculated time . filter 1
15) Draw graph Semitendonosis R with calculated time . filter 2
16) Draw graph P1 trigger with calculated time . filter 3
17) Draw graph R1 trigger with calculated time . filter 4
18) Store in filtered data from filter 1 . filter 2 . filter 3 . filter 4
19) Store in all channels from filtered data
Details of programming for filtering algorithm

![Image of filtering algorithm interface]

- **Object**: filter1
- **Name**: filter1
- **Formula**: `smoothAvgCentered(a,a,b)`
Details of programming for channel selection to calculate on time of EMG

Channel is selected and baseline set against which to compare increase (above 3SD) to calculate on time
Details of programming for calculation of threshold and on time of selected EMG channel

### Object "zerocross" (App. #2)

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Clear</td>
<td>EMG result plot</td>
</tr>
<tr>
<td>2</td>
<td>Calculate</td>
<td>time for emg plot</td>
</tr>
<tr>
<td>3</td>
<td>Calculate</td>
<td>convert to sign</td>
</tr>
<tr>
<td>4</td>
<td>Calculate</td>
<td>zeropoint</td>
</tr>
<tr>
<td>5</td>
<td>Calculate</td>
<td>ontime</td>
</tr>
<tr>
<td>6</td>
<td>Set</td>
<td>on time</td>
</tr>
<tr>
<td>7</td>
<td>Store in</td>
<td>EMG result plot</td>
</tr>
<tr>
<td>8</td>
<td>Calculate</td>
<td>threshold vector for plot</td>
</tr>
<tr>
<td>9</td>
<td>If/Then</td>
<td>clear and plot 1</td>
</tr>
<tr>
<td>10</td>
<td>Clear graph</td>
<td>Biceps Femoris R</td>
</tr>
<tr>
<td>11</td>
<td>Set</td>
<td>Biceps Femoris R(X vs Y)</td>
</tr>
<tr>
<td>12</td>
<td>Draw graph</td>
<td>Biceps Femoris</td>
</tr>
<tr>
<td>13</td>
<td>End If</td>
<td>clear and plot 1</td>
</tr>
<tr>
<td>14</td>
<td>If/Then</td>
<td>clear and plot 2</td>
</tr>
<tr>
<td>15</td>
<td>Clear graph</td>
<td>Semitendinosus R</td>
</tr>
<tr>
<td>16</td>
<td>Set</td>
<td>Semitendinosus R(X vs Y)</td>
</tr>
<tr>
<td>17</td>
<td>Draw graph</td>
<td>Semitendinosus R</td>
</tr>
<tr>
<td>18</td>
<td>End If</td>
<td>clear and plot 2</td>
</tr>
<tr>
<td>19</td>
<td>If/Then</td>
<td>clear and plot 3</td>
</tr>
<tr>
<td>20</td>
<td>Clear graph</td>
<td>P1 trigger</td>
</tr>
<tr>
<td>21</td>
<td>Set</td>
<td>P1 trigger(X vs Y)</td>
</tr>
<tr>
<td>22</td>
<td>Draw graph</td>
<td>P1 trigger</td>
</tr>
<tr>
<td>23</td>
<td>End If</td>
<td>clear and plot 3</td>
</tr>
<tr>
<td>24</td>
<td>If/Then</td>
<td>clear and plot 4</td>
</tr>
<tr>
<td>25</td>
<td>Clear graph</td>
<td>R1 trigger</td>
</tr>
<tr>
<td>26</td>
<td>Set</td>
<td>R1 trigger(X vs Y)</td>
</tr>
<tr>
<td>27</td>
<td>Draw graph</td>
<td>R1 trigger</td>
</tr>
<tr>
<td>28</td>
<td>End If</td>
<td>clear and plot 4</td>
</tr>
</tbody>
</table>

- with a=filterchannel 0 b=start c=stop
- with a="Z1"
- with zeropoint convert to sign
- with a=start b=zeropoint
- to ontime
- from EMG on data set
- with a="Z1" b=on threshold
- with a=channel select
- with time for emg plot , EMG result plot , time for emg plot , threshold vector for pk
- with a=channel select
- with time for emg plot , EMG result plot , time for emg plot , threshold vector for pk
- with a=channel select
- with time for emg plot , EMG result plot , time for emg plot , threshold vector for pk
- with a=channel select
- with time for emg plot , EMG result plot , time for emg plot , threshold vector for pk
- with a=channel select
- with time for emg plot , EMG result plot , time for emg plot , threshold vector for pk
Details of programming for calculation of threshold level above baseline

Object "on threshold" (App. #2)

Name: on threshold

Formula: \( \text{avg}(a) + (\text{stddev}(a)^3) \)

Math Wizard
Algorithm for determination of on time from selected EMG wavedata - converts wavedata (subtracts baseline, converts to sign i.e. below equal or above baseline) then finds index of row in vector – uses this to calculate time of onset based on sampling rate) then plots graph showing wavedata with ontime cursor.

```plaintext
1) Clear EMG result plot
2) Calculate time for emg plot
3) Calculate convert to sign
4) Calculate zeropoint
5) Calculate ontime
6) Set on time
7) Store in EMG result plot
8) Calculate threshold vector for plot
9) If/Then clear and plot 1
10) Clear graph Biceps Femoris R
11) Set Biceps Femoris R(X vs Y)
12) Draw graph Biceps Femoris R
13) End If clear and plot 1
14) If/Then clear and plot 2
15) Clear graph Semitendinosis R
16) Set Semitendinosis R(X vs Y)
17) Draw graph Semitendinosis R
18) End If clear and plot 2
19) If/Then clear and plot 3
20) Clear graph P1 trigger
21) Set P1 trigger(X vs Y)
22) Draw graph P1 trigger
23) End If clear and plot 3
24) If/Then clear and plot 4
25) Clear graph R1 trigger
26) Set R1 trigger(X vs Y)
27) Draw graph R1 trigger
28) End If clear and plot 4
```

Actions:
- EMG result plot
- time for emg plot
- convert to sign
- zeropoint
- ontime
- EMG result plot
- threshold vector for plot
- clear and plot 1
- clear and plot 2
- clear and plot 3
- clear and plot 4

With:
- a=filterchannel 0
- b=start
- c=stop
- a="X1"
- zero point convert to sign
- a=start b=zeropoint
- from EMG on data set
- a="X1" b=on threshold
- a= channel select
- with a= channel select
- with time for emg plot EMG result plot time for emg plot threshold vector for plot
- with a= channel select
- with time for emg plot EMG result plot time for emg plot threshold vector for plot
- with time for emg plot EMG result plot time for emg plot threshold vector for plot
- with a= channel select
- with time for emg plot EMG result plot time for emg plot threshold vector for plot
- with a= channel select
- with time for emg plot EMG result plot time for emg plot threshold vector for plot
- with a= channel select
- with time for emg plot EMG result plot time for emg plot threshold vector for plot
- with a= channel select
Appendix G: Study 3: Participant Information and Consent Forms

The effect of hamstring injury on the longitudinal excursion of the sciatic nerve during the slump test: A preliminary investigation.

PARTICIPATION INFORMATION SHEET

You are invited to take part in a research study. Before you decide it is important for you to understand why the research is being done and what is involved. Please read the following information carefully and take your time to decide whether or not you wish to take part.

What is the project all about?
Nerves continuously slide, lengthen and compress during movements of the body. The fluidness of this movement is often dependant on the structures the nerve passes through; such as muscle and ligaments. One of the possible causes of hamstring injury is as a result of nerve impingement in the lower back, which causes a decrease or loss of nerve supply to the hamstring muscles. This can then cause a decrease in strength of the hamstrings leading to injury. Upon recovery however, the scar tissue forming within the hamstrings can tether the sciatic nerve and compromise its movement through the muscle. This in turn has been reported to be a potential cause of hamstring injury recurrence. No research however, has examined the movement of the sciatic nerve following hamstring injury. In the upper body, the movement of the median nerve in the wrist has been shown to be reduced in patients suffering from carpal tunnel syndrome (CTS).

The movement of the sciatic nerve is commonly assessed by health professionals using the slump test and the straight leg raise test. The slump test was designed to test the movement of the sciatic nerve from head to toe and is therefore often used in examinations of the back and neck. Ultrasound is a reliable, common tool used to examine nerve movement; particularly in the upper limb. Consequently, the aim of this investigation is to evaluate assess the movement of the sciatic nerve in athletes with a hamstring injury, during a modified slump test.

Why have I been chosen?
You have been chosen on the basis that you are an athlete who participates competitively in their chosen sport and who has sustained a hamstring injury within 21 days, as diagnosed by a therapist external to this project. You are also regarded to be in good health other than your hamstring injury.

Do I have to take part?
Taking part is entirely voluntary. If you do take part you will be given a consent form to read and sign. You are free to withdraw at any time without giving a reason or prejudice.
What will I have to do?
Testing will be undertaken at a convenient time during training, at the Human Performance Laboratory, University of Salford. It will take up maximum 60 minutes of your time. Prior to testing you will have the area where you are experiencing pain in your hamstring, imaged using an ultrasound scanner. To do this, you will be requested to lie on your front on a treatment bed and the injury site then scanned using ultrasound.

You will be asked to sit on a seat, which is part of an isokinetic dynamometer (a device which will move your ankle for you while you relax). Only one leg will be tested at a time, using the following manner: your hip will be placed in a normal seating position, whilst your knee will be mid-way between being fully bent and straightened. Your foot shall be placed on a foot hold of the dynamometer while the leg not being tested at that time, shall rest on a support. You will then be asked to slump your shoulders towards your hips. Following this, you will be asked to either look at the ceiling or bring your chin to chest, before the dynamometer is started and it moves your ankle for you. Whilst your ankle is moving, the examiner shall be ultrasound scanning your sciatic nerve in the back of your thigh. You shall do 3 trials whereby you look at the ceiling and 3 trials where you bring chin to chest. The opposite leg shall then be tested in the exact same manner.

Is there any risk involved?
The risk involved is minimal as the testing procedure used (slump test) is a clinical technique used as a treatment tool in hamstring injuries.

Potential benefits to participants.
By participating in this study you will obtain an assessment of the injury to your hamstring muscle and determine whether the muscle itself has actually experienced damage.

Who will see my details and results?
All identities and information obtained during this study will of course remain strictly confidential. The final results of the study will be available to you, and may be published. No players will be identified in any reports generated. You are free to decide not to be in this trial or drop out at any time. Please feel free to ask any questions about the nature or demands of the project at any time.

Researcher’s name: Elizabeth Fowler
Email: E.M.Fowler@pgr.salford.ac.uk

Supervisors: Dr. Lee Herrington
Email: l.e.herrington@salford.ac.uk
Dr. Steve Pearson
Email: s.pearson@salford.ac.uk
CONSENT FORM

Title of Project: The effect of hamstring injury on the longitudinal excursion of the sciatic nerve during the slump test: A preliminary investigation.

Name of Researcher: Elizabeth Fowler
Supervisor: Dr. Lee Herrington

Please initial box

1. I confirm that I have read and understand the information sheet dated....................for the above study.

2. I understand that my participation is voluntary and that I am free to withdraw at any time prior to or during testing.

3. I agree to take part in the above study.

Name of patient Date Signature

Elizabeth Fowler Date Signature

(1 copy for patient, 1 copy for researcher)
Appendix H: Study 4: Participant Information and Consent Forms

Location of sensations experienced during the slump test and inter-segmental mobility of the lumbar spine in athletes with a clinically diagnosed hamstring strain.

PARTICIPATION INFORMATION SHEET

You are invited to be involved in a study which forms the research part of a PhD degree in Sports Injury. Before you decide to take part, it is important for you to understand this piece of research and what is involved. Please read the following information carefully and take your time to decide whether or not you wish to take part.

What is the project all about?
Assessing the mobility of individual segments or vertebra within the spine is important in patients presenting with pain or discomfort in the lower back, as it allows clinicians to determine which vertebra can be contributing to the patient’s symptoms. In patients with low back pain, the movement between the vertebrae can become very limited or stiff, or alternatively, become too mobile; both conditions which can cause pain or discomfort. Alteration in movement of the spine is not only present in individuals with back pain, but it is suggested it is also present in people who suffer from hamstring injury. Research has suggested that any condition affecting the lower back or the nerves around this region, can cause pain in the hamstrings on the back of the thigh, and possibly lead to injury of this muscle group. However, no research has been done to see if the mobility of the lower back is affected during hamstring injury.

Clinicians assess the mobility of the vertebra in the spine using “accessory motion testing”. This involves the therapist placing pressure down through one single vertebra using their thumbs or hands and feeling how well that specific vertebra moves in relation to the vertebrae above and below it. Whilst a very effective method in diagnosing and treating patients with low back symptoms, it can be unreliable between therapists as it is dependent on each therapists interpretation as to what “stiffness”, “normal” and “excessive movement” of a spinal vertebra means. Part of this study will evaluate the mobility of the lumbar spine (low back) in individuals with a current hamstring strain (within 21 days of hamstring injury onset).

Whilst feeling the movement of the spine is important for clinicians, a clinical test which assesses the sensitivity of the nerves around the spine and into the legs is also of importance, particularly in hamstring injured athletes as it helps a therapist determine whether some of the patient’s symptoms are arising from the nervous system. To do this, a therapist will typically wish to establish the location of a patient’s symptoms during the slump test to gain a full clinical impression as to the origin of an injured athlete’s symptoms. Consequently, a second aspect of this study is to determine where hamstring injured athletes typically experience symptoms during the slump test.
Why have I been chosen?
You have been chosen on the basis that you are suffering from a hamstring injury which occurred within the past 21 days, as diagnosed by your club physiotherapist and club doctor.

Do I have to take part?
Taking part is entirely voluntary. If you do take part you will be given a consent form to read and sign. You are free to withdraw at any time without giving a reason or prejudice.

What will I have to do?
Testing will be undertaken at a convenient time at your club which will take up a maximum 45 minutes of your time. Firstly, you will be asked to mark on a body chart where you have been experiencing pain, symptoms or sensations in your body since the hamstring injury occurred.

You will then be asked to lie on your front, on a treatment couch. You will be asked to expose your lower back only by raising the clothing around your lower back up slightly so the therapists has access to this area. The therapist will place their thumbs or palm of their hand onto your lower spine only. At each part of the spine (for 5 vertebrae) they will gently push down through your spine so they can determine if your spine is very mobile, normal or stiff. The movement they will execute is minimal and little force is exerted through the movement. However, for each vertebra the therapist will ask you if you experience any discomfort with the movement. Please answer with a simple “yes” or “no”.

You will also be requested to undertake the slump test. You will be asked to sit on a table with the back of your knees against the edge of the table. You will then be asked to slump your shoulders towards your hips. You will then be required to bring your chin to your chest after which, the examiner will apply some overpressure (via hand) to your head and neck. The examiner will then raise your foot up towards you and subsequently straighten your knee, to a point where the examiner experiences resistance of the limb to the movement. Whilst momentarily in this position, you will be asked to dictate to the examiner’s assistant, the locations of your body where you feel any sensations, symptoms or pain. The examiner will then release your neck and ask you to look upwards towards the ceiling, where you will be asked again to dictate the locations of your body where you feel pain/sensations/symptoms. Three trials will be taken on each leg for both neck positions.

Is there any risk involved?
The risk involved is minimal as the testing procedure used is a standard part of a lumbar spine assessment and the slump test is an integral part of assessing, diagnosing and treating hamstring strains.

Potential benefits to participants.
By participating in this study you will obtain an assessment as to the mobility of the vertebrae in your lumbar spine and also of the locality of symptoms you experience.
during both aspects of the slump test. This may be particularly beneficial if you partake in sports as stiff vertebrae within the lumbar spine has been associated with disc degeneration, which in turn has been proposed as a contributing factor for hamstring injury.

**Who will see my details and results?**
All identities and information obtained during this study will of course remain strictly confidential. The final results of the study will be available to you, and may be published. No details of participants will be identified in any reports generated. You are free to decide not to be in this trial or drop out at any time. Please feel free to ask any questions about the nature or demands of the project at any time.

Researchers' name: Elizabeth Fowler  
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CONSENT FORM

Title of Project: Location of sensations experienced during the slump test and inter-segmental mobility of the lumbar spine in athletes with a clinically diagnosed hamstring strain.

Name of Researcher: Miss Elizabeth Fowler

Please initial box

1. I confirm that I have read and understand the information sheet for the above study.

2. I understand that my participation is voluntary and that I am free to withdraw at any time without my medical care or legal rights being affected

3. I agree to take part in the above study.

Name of patient ___________________________ Date __________ Signature __________

Researcher ___________________________ Date __________ Signature __________

(I copy for patient, 1 copy for researcher, 1 copy to be filed in notes)
Appendix I: Lumbar mobility as measured using a central post accessory motion:
SUBJECT NUMBER: ________

Please mark the subject number above and circle your answers below for each of the three spinal levels.

<table>
<thead>
<tr>
<th>Q1 Mobility rating</th>
<th>L1</th>
<th>L2</th>
<th>L3</th>
<th>L4</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Hypomobile</td>
<td>Hypomobile</td>
<td>Hypomobile</td>
<td>Hypomobile</td>
</tr>
<tr>
<td></td>
<td>Normal</td>
<td>Normal</td>
<td>Normal</td>
<td>Normal</td>
</tr>
<tr>
<td></td>
<td>Hypermobile</td>
<td>Hypermobile</td>
<td>Hypermobile</td>
<td>Hypermobile</td>
</tr>
<tr>
<td>Q2 Discomfort produced at level?</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Q3 What spinal level was marked?</td>
<td>L1</td>
<td>L2</td>
<td>L3</td>
<td>L4</td>
</tr>
</tbody>
</table>
Appendix J: The body chart
Appendix K: Conference Presentations

May 2009

Salford Postgraduate Annual Research Conference

Conference presentation: *Can the slump test be used as a predictive tool for hamstring injury?*

Chair Dr. Laurence Kenny.

November 2010

British Association of Sports Rehabilitators and Trainers symposium

Poster Presentation: *Hamstring injury and longitudinal excursion of the sciatic nerve during the slump test.*

(Poster can be viewed overleaf).

Winner of the “Best Poster” competition

Chair Mr. Steve Aspinall.
Hamstring injury and longitudinal excursion of the sciatic nerve during the slump test

University of Salford, U.K.

Background
Scar tissue has been proposed to 'tether' the sciatic nerve in the posterior thigh in athletes presenting with hamstring strains (Turl and George, 1998). This tethering may reduce mobility of the sciatic nerve and give a subsequent positive slump test. No research to date has investigated the effect hamstring injury has on the sciatic nerve in the posterior thigh.

Aim
The aim of this study is to present preliminary findings on the potential effect of hamstring injury on the longitudinal excursion of the sciatic nerve in the posterior thigh, measured during the slump test.

Methods
Longitudinal sciatic nerve excursion was determined during a modified slump test in six healthy, asymptomatic males (mean ± SD age = 30 ± 9.6 years) and three males with current clinically diagnosed hamstring strains (mean ± SD age = 23 ± 2.6 years). An isokinetic dynamometer was utilised in passive mode (10°/sec) to conduct a modified slump test, where the ankle joint was the structural differentiating manoeuvre (Figure 1).

Figure 1: Experimental protocol. With the hip and knee placed in 90° and 50° flexion respectively, the participant maintained thoracic flexion and either cervical flexion or extension. The ankle joint was then passively moved by the dynamometer 10° into plantar-flexion or dorsiflexion from a neutral position.

B mode ultrasonography was used to record the movement of the sciatic nerve in the posterior thigh during the slump test, in addition to determining the absence or presence of a muscle strain within the posterior thigh in the injured cohort. An independent clinician with experience in musculoskeletal ultrasound conducted the diagnostic analysis of the posterior thigh. An adaptive block matching algorithm using cross-correlation was utilised to dynamically track the movement of the sciatic nerve, during both isolated movements of the ankle joint (Figure 2). Excursion of the nerve was measured during a total of 20° dorsiflexion and 20° plantarflexion.

No statistical analysis was undertaken due to limited subject numbers.

Figure 2: Ultrasound image of the Region of Interest (ROI) of the sciatic nerve being examined using the cross-correlation algorithm.

Results
Only one participant with a clinically diagnosed hamstring strain showed any evidence of hamstring muscle damage (Figure 3).

Figure 3: Haematoma (circled) in close proximity to the sciatic nerve in the posterior mid-thigh, thereby constituting a positive hamstring muscle strain.

Little difference existed between the magnitude of longitudinal sciatic nerve excursion between the control and injured groups (Figure 4). The athlete with an ultrasonography-confirmed hamstring strain did not have reduced nerve excursion compared to those athletes with a negative scan.

Figure 4: Mean (with standard error of mean) longitudinal excursion of the sciatic nerve during the slump test in healthy individuals and hamstring injured athletes. CE+PF = cervical extension*20; ankle plantar flexion; CE+DF = cervical extension*20° ankle dorsiflexion; CF+PF = cervical flexion*20° ankle plantar flexion; CF+DF = cervical flexion*20° ankle dorsiflexion.

Conclusion
In this preliminary study, the presence of hamstring strain or posterior thigh injury, at least to the extent seen here, does not appear to affect sciatic nerve longitudinal excursion in the posterior thigh during the slump test. The hypothetical 'tethering' of the nerve during hamstring injury must be questioned, as it required significant muscle damage in Carmody and Pretto's (1995) case study to cause entrapment of the sciatic nerve following hamstring injury. Additionally, for tethering to occur to the nerve, the haematoma must surely encompass the nerve segment, a factor which may not necessarily occur due to the variability of the location of actual muscle damage during hamstring strains (Asklmg et al., 2000).

References