

**An assessment of the clinical application and utility of the Babinski sign
using objective kinematic and electromyographic methods**

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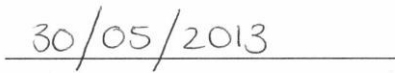
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Declaration

I, Chloe Lynn Dafkin declare that this dissertation is my own work, except to the extent indicated in the acknowledgements or contributions sections. It is being submitted for the degree of Master of Science in the University of the Witwatersrand, Johannesburg. It has not been submitted for any other degree or examination in this or any other university.

A handwritten signature in black ink, appearing to read 'Chloe', is written over a horizontal line.

(Signature of Candidate)

The date '30/05/2013' is handwritten in black ink over a horizontal line.

(Date)

Abstract

The Babinski sign is a pathological response elicited by a stimulus to the lateral plantar border of the sole of the foot. The resulting reflex involves dorsiflexion (upward motion) of the toes, most notably the hallux, with accompanying flexion in the ankle, knee and hip. It is an important part of the clinical neurological examination and aids in the diagnosis of central nervous system dysfunction. There is however no wholly standardised method to elicit this reflex or interpret it, resulting in possible variation in its utility. The resulting aim of the studies constituting this dissertation were therefore to: 1) assess what techniques and pressures are used to elicit the reflex in a group of neurologists; 2) to investigate the relationship between input variables of the reflex and the resultant output variables as measured with the use of electromyography and kinematics; 3) compare objective variables, relating to toe, foot and leg movement, of the pathological reflex to the healthy response; 4) assess the inter-rater reliability of the reflex and 5) determine what aspects of the reflex are most closely related to the ratings of the students and neurologists.

A specialized custom-built Babinski hammer was constructed to measure the duration of the stroke and pressures exerted on the foot of a single healthy subject by neurologists (n=12). The relationship between the recorded pressures and the movement of the toes (measured kinematically), muscle activity in the *tibialis anterior* and the pain felt by the subject (gauged using a visual analogue scale) were evaluated. Following this, the average pressure used by the neurologists was used to elicit the reflex in six patients with known positive Babinski responses and six healthy gender and age matched controls. These reflexes were compared with kinematic (measurement of toe, foot and leg movement) and electromyographic (muscle activity of the involved muscles) methods. These reflexes were recorded and the recorded footage was shown to 12 medical students and 12 neurologists who were asked to interpret if

the responses were pathological or non-pathological. Kinematic and electromyographic descriptions of each reflex made it possible to assess what aspects of the reflex are important for classification of a pathological response for both medical students and neurologists.

A large amount of intra- and inter-rater variability was shown amongst the neurologists in how they elicited the reflex. The amount of pressure applied was shown to be significantly related to hallux movement ($p < 0.01$) as well as to the degree of pain felt by the subject ($p < 0.01$). Significant differences were found between the patients and controls for change in hallux angle ($p < 0.0001$), movement latency ($p < 0.05$) and the maximum electromyographic amplitude of *tibialis anterior* ($p < 0.01$). The inter-rater reliability of the medical students and the neurologists showed substantial agreement between raters ($\kappa = 0.67$ and 0.72 respectively). Both neurologists and students made use of the change in hallux angle, time taken to reach maximum ankle angle, movement latency and the maximum amplitude of *gastrocnemius* when rating the reflex. Neurologists alone observed time taken to reach maximum hallux angle and change in ankle angle as being important while medical students' alone looked at maximum amplitude of *biceps femoris*.

In conclusion, I found a large variation between the techniques of neurologists when assessing the Babinski reflex. This variation is related to variation in aspects of the resultant reflex. The pathological response (the Babinski sign) has shorter movement latency and less activity in the *tibialis anterior* muscle than the flexor response seen in healthy individuals. Ratings of pre-recorded Babinski responses had substantial agreement when both neurologists and medical students assessed pathology. In order to assess them both groups made use of the speed of the reflex, the direction of hallux movement and concurrent withdrawal activity in the leg to differentiate between a pathological and a healthy response.

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Abbreviations

BMI	Body mass index
EMG	Electromyography
HREC	Human Research Ethics Committee
IQ	Interquartile
L4	Fourth lumbar dermatome
L5	Fifth lumbar dermatome
LMN	Lower motor neuron
MRI	Magnetic resonance imaging
N Path	Neurologists pathological
N NPath	Neurologists non-pathological
NREM	Non-rapid eye movement
S1	First sacral dermatome
S2	Second sacral dermatome
S3	Third sacral dermatome
SD	Standard deviation
S Path	Students pathological
S NPath	Students non-pathological
UMN	Upper motor neuron
VAS	Visual analogue scale

Contributions to the project

As part of the required declaration of this dissertation, I acknowledge contributions by various individuals to this work as detailed below.

The experimental design was devised by myself, with the assistance of my supervisors, WarrickMcKinon and Samantha Kerr, for all work described in this dissertation.

WarrickMcKinon and I were responsible for the laboratory design, camera mounting and the development of some kinematic analysis tools.

WarrickMcKinon, Alex Erwin and I designed and constructed the customized Babinski hammer.

All data collection and analysis was performed by me.

Algorithms for the entire kinematics process were written by WarrickMcKinon, Andrew Green and I.

Details of three manuscripts which have been prepared for submission can be found in Appendix VI. Details of a further two papers which I published during my candidature for this degree can be found in Appendix VII.

Introduction

In the introduction to this dissertation I will firstly briefly discuss the historical context of what became known as the Babinski sign, followed by a background to Joseph Babinski and the Babinski reflex itself. Following that is a description of the current understanding of the Babinski reflex and how this reflex is elicited and interpreted in a clinical setting. I then discuss the practical uses of the Babinski reflex. A brief introduction to two fields that are central to this dissertation, namely electromyography and kinematics, then follows. Lastly, the introduction ends with a rationale for the current studies as well as the aims of the studies making up this dissertation.

1.1. Background to clinical neurology and the Babinski reflex

1.1.1. The clinical usefulness of neurology

Clinical examination of patients began playing an important role in neurology during the 19th century (van Gijn J, 1996a). Before this time, contact with the patients was reserved for surgeons (van Gijn J, 1996a). Not much was known about brain injuries or spinal injuries although the anatomy of the brain was known (Lanzino *et al*, 1997). In the 1800's Physicians could only make use of this knowledge of the brain for diagnostic purposes with the development of procedures to test the functioning of the brain and spinal cord. This brought about the discovery of spinal reflexes and what pathologies their elicitation could help diagnose. Reflexes were also found to aid in the localization of damage to the brain and spinal cord which allowed improvements in treatments due to a greater understanding of what areas were affected (Lanzino *et al*, 1997). The second half of the 19th century saw the discovery of ankle clonus and spasticity, cutaneous reflexes and their disappearance in hemiplegia, many tendon reflexes and the Babinski reflex. The use of reflexes has made non-invasive differentiation between upper motor neuron (UMN) and lower motor neuron (LMN) lesions possible. UMN lesions present with increased reflex responses while LMN lesions present with decreased reflex responses (Berne and Levy, 2010). It is important to

differentiate between UMN and LMN damage as the treatments and surgical options differ between the two and in order to receive timely and correct treatment a correct diagnosis needs to be made. One of the most well-known and important diagnostic differences between UMN and LMN lesions is the presence or absence of the Babinski sign (Berne and Levy, 2010).

1.1.2. Joseph Babinski

Joseph Jules Francois Felix Babinski was born in Paris, France on the 17th of November 1857 (Bassetti, 1995). His interest in neurology first came about when he worked under Edme Vulpian, the famous clinical neurologist (Lanzino *et al*, 1997), and was later complimented by Babinski's work under Jean Charcot at La Salpêtrière (Kakitaniet *al*, 2010).

Joseph Babinski's most famous contribution to neurology is doubtlessly his discovery/documentation of the Babinski sign (Lanzino *et al*, 1997). Before Babinski's famous paper of 1896 (Babinski, 1896) little was known of the plantar reflex or pyramidal syndrome. Spasticity and clonus had already been found to show pyramidal syndrome (Charcot, 1876) as had the hyperreflexia of tendon reflexes (Erb, 1875). All that was known of the plantar reflex was that stimulation to the sole of the foot produced a withdrawal response (cited by van Gijn, 1996a). Babinski first presented his "toe phenomenon" (figure 1.1) in a short 28 line presentation to the Biological Society of Paris in 1896 (Babinski, 1896). This first paper compared the response on the affected to the response of the healthy side of patients with hemiplegia (Babinski, 1896). He described that all the toes on the affected side would extend upwards upon the pricking of the sole (Babinski, 1896).



Figure 1.1: Images of Babinski’s description of the “toe phenomenon”from his 1898 publication.

Two years later, in 1898, he wrote another paper in which he emphasized that the up going extension of the hallux was the most diagnostically important part of the sign (Babinski, 1898). It was only in this paper that he mentioned stroking the sole of the foot in order to achieve the response as well as suggesting a relationship between the up going toe and damage to the pyramidal tracts (Babinski, 1898). Following these publications were a lot of confirming studies from around the world of the link between the toe phenomenon and afflictions of the pyramidal system as well as numerous rival methods of eliciting the up going toe response (van Gijn, 1996a, Kumar and Ramasubramanian, 2000, Kakitani *et al*, 2010). In 1903 Babinski published another paper on the sign adding a new attribute, the fanning of the toes (van Gijn, 1996a). In this latter paper Babinski also spoke about eliciting the reflex on normal people and how the upward movement of the toes was rarely ever present (Bruno *et al*, 2007).

Along with the Babinski sign, Babinski made many other contributions to clinical neurology (Lanzino *et al*, 1997) particularly focusing on differentiating between hysteric and organic conditions (Bassetti, 1995, Lanzino *et al*, 1997, Kakitani *et al*, 2010). He also made very

important contributions to neurosurgery (Lanzino *et al*, 1997). Babinski was one of the first people to describe how surgical decompression could be used to reduce intracranial pressure and wrote many papers on the diagnosis and surgical treatment of brain tumours (Lanzino *et al*, 1997). Babinski also played an essential role in founding the Société de Neurologie de Paris (Lanzino *et al*, 1997). Joseph Babinski died in 1932 at the age of 75 (Kumar *et al*, 2000) after lengthily suffering from Parkinson's disease (Bassetti, 1995). This is not a complete history of either Babinski or his reflex. More detailed accounts of the works and life of Babinski can be found in Bassetti (1995), van Gijn (1996a), Bruno *et al* (2007) and Pauc (2011).

1.2. The Babinski reflex

1.2.1. The normal response elicited as a result of stimulation of the plantar surface of the foot

The pyramidal tracts are made up of the corticospinal and corticobulbar tracts (Khurana, 2006). Unlike the corticobulbar tracts, which innervate cranial nerves, the corticospinal tracts hold axons that project from the motor cortex of the brain through the corona radiata and the internal capsule (Deng *et al*, 2012) to the spinal cord motor system (Bray *et al*, 2005). These corticospinal tracts are the pathways through which a majority of the regulation of discrete voluntary movements by the motor cortex occur (Khurana, 2006). The neurons of the motor cortex and axons that project to the corticospinal tract form part of a functional classification of neurones, known as the upper motor neurons (UMN) (Berne *et al*, 2010). These UMN then connect with lower motor neurons (LMN) which consist of alpha and gamma motor neurons which project to extrafusal and intrafusal muscle fibers respectively (Adams and Hicks, 2005). Of importance to the current dissertation is that the descending corticospinal tracts affect a reflex in many ways (Berne *et al*, 2010). Their influence could be direct to the alpha

or gamma motor neurons, act on other segmental levels of the spinal cord through propriospinal neurons or indirectly by activating inhibitory interneurons (Berne *et al*, 2010).

One reflex that is influenced by descending UMN activity is the plantar withdrawal reflex (the flexion of a limb in response to a painful stimulus, c.f. standing on a pin). Each area of skin has a specific withdrawal reaction to painful stimuli in order to remove the limb from the stimulus (Grimby, 1963, Walker *et al*, 1990). One such area is the S1 dermatome which is the receptive field for the plantar reflex (Kumar *et al*, 2000). The plantar reflex is the response brought about by stimulating the S1 dermatome (lateral plantar border of the sole of the foot). This results in plantar flexion of the toes (flexing towards the plantar surface), dorsiflexion of the foot (flexing towards the dorsum) and flexion of the knee and hip (Kugelberget *al*, 1960). The plantar flexion of the toes however is not part of the withdrawal of the lower limbs seen in the plantar reflex but is a monosegmental skin reflex that occurs from touching the skin on the sole of the foot. Defects to the pyramidal tracts will change the response and result in presentation of the Babinski sign which is discussed hereafter.

1.2.2. Pathophysiology and the occurrence of the Babinski sign

The Babinski sign is characterised by dorsiflexion of the great toe, with or without fanning of other toes, and withdrawal of the leg on plantar stimulation (Pauc, 2011). The movement is greatest in the hallux due to its anatomical structure which allows a larger spectrum of movement (van Gijn, 1995). The Babinski sign has been found to occur in response to UMN damage in the pyramidal tracts of the fibers that project to the foot muscle motoneurons (van Gijn, 1995, Ditunno and Bell, 1996). For this reason the most common finding together with the up going toe is weakness of foot movement (van Gijn, 1978, Raijmakers *et al*, 1991, Ditunno and Bell, 1996). UMN damage has also been found to be associated with increases in the receptive field area for the plantar reflex from dermatome S1 to include dermatomes

S2, S3, L4 and L5 (Kugelberg *et al*, 1960, Nakanishi *et al*, 1974, Walker *et al*, 1990, Bruno *et al*, 2007 and Kuruvilla and Wattamwar, 2011). This means that the reflex can be elicited not only from the lateral sole of the foot but from the entire foot, the lower half of the leg and as far superior as the top of the thigh. In conjunction with the increased receptive area, damage to the pyramidal tracts also decreases the threshold needed to activate the reflex response (Nakanishi *et al*, 1974, Roby-Bramiet *et al*, 1989, Kuruvilla and Wattamwar, 2011).

UMN damage can be caused by structural lesions or metabolic lesions. Structural lesions could be initiated by an interruption in the blood supply to UMNs (a stroke) (Khurana, 2006, Milanov and Georgiev, 1994), myelopathy (Cook *et al*, 2007), spinal cord injuries (Little *et al*, 1989, Aydin, 2005, and Benz *et al*, 2005) or neurodegenerative diseases (Mayer, 1997). Metabolic lesions could be due to aging (McCance *et al*, 1968), hypoglycaemia (Nathan and Smith, 1955), epileptic seizures (van Gijn, 1995), general anesthetic (Nathan and Smith, 1955), NREM sleep (Fujiki *et al*, 1971, Yokota *et al*, 1991, Smith, 1987 and Kumar and Ramasubramanian, 2000) and from some medications (Kumar and Ramasubramanian, 2000). No precise relationship has been shown between the anatomical condition of the pyramidal tracts and the presence or absence of the Babinski sign (Nathan and Smith, 1955). This may be due to the Babinski sign being caused by not only structural lesions, which would be visible on a magnetic resonance imaging (MRI) scan or upon autopsy, but also metabolic lesions which would not be visible on a MRI scan or easily detectable on autopsy (Nathan and Smith, 1955). However Nathan and Smith's (1955) theories of the relationship between the Babinski reflex and the pyramidal tracts were seriously questioned by Walshe (1956).

Damage to these UMN brings about UMN syndrome (Khurana, 2006). The symptoms of UMN syndrome have been divided into positive and negative symptoms (Mayer, 1997). Those symptoms classified as positive include spasticity and released flexor reflexes in the lower limbs (the Babinski sign) (Mayer, 1997). The negative symptoms are weakness and

loss of dexterity (Mayer, 1997). A common cause for most of these symptoms is increased activity of the motor control systems (Berne *et al*, 2010).

There are however cases in which there is proven damage of the pyramidal tracts and an absent Babinski sign (van Gijn, 1996a, Petersen and Schubert, 2010). The reason for the lack of Babinski sign manifestation is likely a dysfunction at some point along the segmental reflex pathway (van Gijn, 1996a) such as loss of sensation to the S1 dermatome or paralysis of the muscles used to extend the hallux (Kumar and Ramasubramanian, 2000). Note that spinal shock and certain drugs (e.g.: parenteral physostigmine) are known to also eliminate the Babinski sign (Kumar and Ramasubramanian, 2000).

1.2.3. Muscle activity

The muscles that have been shown to take part in the pathological Babinski reflex response are the *extensor hallucislongus*, *tibialis anterior*, *extensor digitorumlongus*, *biceps femoris* and the *tensor faciae latae* (Kumar *et al*, 2000). The unique electromyographical (EMG) feature of the Babinski reflex that separates it from the normal flexor plantar response is recruitment of the *extensor hallucislongus* with the contraction of the *tibialis anterior* and the *extensor digitorumlongus* (Landau and Clare, 1959, van Gijn, 1975, van Gijn, 1976). The *extensor hallucislongus* is the muscle responsible for the up going toe (van Gijn, 1995). It is a very deep set muscle and is covered by the *tibialis anterior* as well as the *extensor digitorumlongus* (Roby-Bramiet *al*, 1989). For this reason it is very difficult to obtain accurate electromyographic data from the *extensor hallucislongus* with the use of surface electromyography (van Gijn, 1975, Roby-Bramiet *al*, 1989). Needle electrodes are therefore most often used when assessing the activity in this muscle (Kugelberg, 1948, Kugelberg *et al*, 1960, Grimby, 1963, Nakanishi *et al*, 1974, van Gijn, 1975, van Gijn, 1976 and Uysa *et al*,

1999). However the use of needle electrodes does cause pain to the participant and could add artificial stimulation to the reflex (Landau and Clare, 1959).

Research of the muscles utilized in the reflex response has shown that an action potential in the pathological response of the *extensor hallucis longus* and the *tibialis anterior* occur simultaneously (van Gijn, 1976). Grimby (1965) showed that the reflex pattern is made up of both flexor and extensor muscle activity of the toes. In the normal condition the flexor response dominates whilst with damage to the pyramidal tracts the extensor response dominates (Grimby, 1965). However Grimby (1965) made use of an electrical stimulation to the sole of the foot and this has been shown to cause dorsiflexion of the toes even in normal healthy people (van Gijn, 1975). Furthermore Kugelberg (1948) has shown, through the use of EMG, that the flexion reflex is mediated by both A-fibers (fast conducting, myelinated fibers) and C-fibers (slow conducting, unmyelinated fibers).

The latency (time taken between the stimulus and the initiation of muscle activity) of the muscle response has also been looked at in past studies. The latency can only be accurately assessed when an electrical stimulus is used to elicit the reflex (Ugawa *et al*, 1996). However in clinical practice/research a mechanical stimulus is often preferred (reasons discussed in section 1.3.1) and thus the latency is not always obtainable (especially in the everyday clinical setting). The latency values for *tibialis anterior*, *gastrocnemius*, *rectus femoris* and the medial hamstrings have been shown not to differ between spinal cord injury patients (displaying a positive Babinski response) and normal controls (Deutsh, 2005). Latency has also been used in studies in order to exclude voluntary movement (Nakanishi *et al*, 1974, Grimby, 1963 and Uysa *et al*, 1999) as a short latency value most likely represents a spinal reflex response (Nakanishi *et al*, 1974).

1.2.4. Flexion synergy

The entire withdrawal reflex response of the leg from a noxious stimulus applied to the sole of the foot displays a phenomenon known as flexion synergy (van Gijn, 1996a, Bruno *et al*, 2007). This involves synergistic movements of the hip, knee, ankle and toes (van Gijn, 1995). It is widely accepted that the Babinski sign is part of this flexion synergy (Sherrington, 1910, Walshe, 1914, Walshe, 1956, Kugelberget *al*, 1960, van Gijn, 1995, van Gijn, 1996a, Mayer, 1997, Kumar *et al*, 2000, van Gijn, 2002, van Gijn, 2003, Bruno *et al*, 2007, van Gijn, 2010, Pauc, 2011, Deng *et al*, 2012,). However Babinski himself believed that the pathological up going toe response was an alteration to the normal flexion synergy which involved the plantar flexion of the toes (Bassetti, 1995). Hoff and Breckenridge (1956) agreed with this interpretation and stated that the Babinski response and the withdrawal reflex were two separate and distinct responses based on studies in decerebrate animals. However various inaccuracies and gaps in the Hoff and Breckenridge (1956) study references have been reported (Bassetti, 1995). Conversely Sherrington (1910) showed that the Babinski reflex and the withdrawal reflex were the same reflex. This view has received support in subsequent studies (Kugelberg, 1948, Landau and Clare, 1959, Kugelberget *al*, 1960). Therefore current understanding would hold that the Babinski sign is an intricate part of flexion synergy of the lower limbs.

The pathological withdrawal reflex comes about when there is damage to the pyramidal tracts resulting in a release of the flexor response (Mayer, 1997). This response is elicited at the foot but involves many limb segments innervated from further up the spinal cord (Mayer, 1997). This innervation works to shorten the limb (van Gijn, 1995). Initially it was believed that the down ward movement of the toes was part of this flexion synergy as it is activated by anatomical flexors of the toes (Hoff and Breckenridge, 1956). Today, the current paradigm contends that the anatomical extensors of the toes are thought to be physiological flexors as

they actually act to shorten the limb (Walshe, 1914), moving the foot into a more proximal orientation overall. This can be seen when imagining a person standing on their toes in order to lengthen their legs. Therefore the Babinski sign is just a return to the primitive withdrawal response seen in infants (Zafeiriou, 2004). The infant plantar response is discussed below.

1.2.5. *The plantar reflex in infants*

In infants up until one year of age stimulation to the sole of the foot brings about retraction of the whole leg involving flexion at the hip, knee and ankle (van Gijn, 2002). This is also accompanied by dorsiflexion of the toes which resembles the Babinski sign (Andrews and Fitzgerald, 2000, van Gijn, 2002). The pyramidal tracts are not fully developed at birth therefore the plantar reflex in infants supports the theory that the up going toe movement in adults is a result of pyramidal tract underdevelopment/ineffectiveness (van Gijn, 1977). The fibers that make up the pyramidal tract are unmyelinated at birth and only commence myelination approximately two weeks post-partum (Khurana, 2006). Full myelination can take as long as two years to complete (Khurana, 2006). As the infant grows the pyramidal system matures and two changes are made to the plantar reflex (van Gijn, 2002). These changes are: the withdrawal of the limbs becomes less brisk and the extensor toe movement is now replaced with flexor toe movements (van Gijn, 2002).

Despite the above knowledge of the plantar response, a large variation in the plantar response has been shown to exist in infants. Jaynes *et al* (1997) showed that 90% of infants have an extensor response of the toes and found no asymmetrical responses. An asymmetrical response is characterised by a different toe response being obtained from each foot of the same infant. In contrast, other studies have found high levels of asymmetrical responses and inconsistencies and thus recommended removing the evaluation of the plantar reflex from the neonatal neurological exam (Gupta and Gupta, 2003). Moreover the evaluation of the plantar

reflex may only be truly clinically useful after the first year following birth to discover a neurological disorder (Kumhare *et al*, 2002). This is because up until one year after birth the reflex has been found to be either flexor, extensor or equivocal as the infant is transitioning from the abnormal extensor response to the normal flexor response seen in adults (Kumhare *et al*, 2002). The variation in the results from these studies could be due to the technique used to elicit the response (Bodensteiner, 2004). In infants the stimulus must be nociceptive and shouldn't involve the application of pressure to the sole (Gupta and Gupta, 2003, Bodensteiner, 2004). Pressure to the sole results in a competing reflex response found in infants, namely the plantar grasp reflex (van Gijn, 1977, Gupta and Gupta, 2003, Bodensteiner, 2004 and Pauc, 2011). As its name suggests this reflex involves the infant grasping with their foot which leads to plantar flexion of the toes (van Gijn, 1977).

As with eliciting the reflex in infants, there are certain theories on the technique of eliciting the Babinski reflex in adults as well as how to interpret the response.

1.3. Clinical procedure

1.3.1. Procedure for eliciting the Babinski reflex

To elicit the Babinski reflex in clinical practice the patient is usually in the supine position (Walker *et al*, 1990). The patient should be warned that the foot will be scratched and told to keep the leg relaxed to avoid a voluntary withdrawal response caused by the surprise of having a pressure applied to the foot (van Gijn, 1995). A 'semi sharp' object is run along the lateral plantar border, from the heel up across the transverse arch (Dohrmann and Nowack, 1973, Walker *et al*, 1990, van Gijn, 1995 and Kumar *et al*, 2000). The reason the lateral border of the sole is used is because it has been shown to be more sensitive than the medial plantar surface of the foot to producing an extension of the hallux (Kugelberg *et al*, 1960). The stroke should be slow, with a total duration of between five and six seconds

(Dohrmann and Nowack, 1973, Walker *et al*, 1990). Note that the stimulus does not need to be painful to elicit the extensor response in a patient with pyramidal tract damage (Roby-Bramiet *al*, 1989).

A scratching stimulus or a moving pressure has been shown to be the best method for eliciting the Babinski response (Roby-Bramiet *al*, 1989). This is presumably due to stroking generating summation of action potentials in the muscles accountable for the response (Roby-Bramiet *al*, 1989). The reflex response may differ depending if the method of stimulation is electrical or mechanical (Nakanishi *et al*, 1974, van Gijn, 1975). Electrically stimulating the Babinski reflex through the use of needle electrodes in the sole of the foot has been known to cause activity in the *extensor hallucis longus* muscle in normal healthy people where mechanical stimulation did not (van Gijn, 1975). For this reason a stroking mechanical stimulus may be considered to be more accurate and more representative of the clinical conditions than an electrical stimulus (Nakanishi *et al*, 1974, van Gijn, 1975, Bassetti, 1995 and van Gijn, 1996a). Nevertheless electrical stimulation has been used in many studies to elicit extensor toe movement (Kugelberget *al*, 1960, Grimby, 1963, Grimby, 1965, Nakanishi *et al*, 1974, van Gijn, 1975 and Deutsch *et al*, 2005). This is most likely due to its controllable, measurable properties and the fact that electromyographic latency can be calculated with the use of an electrical stimulus (Ugawa *et al*, 1996).

Mechanical stimulation has also been used in many research studies due to it mimicking the clinical condition (van Gijn, 1975, van Gijn, 1976, van Gijn, 1978, Estanol, 1983, Little *et al*, 1989, Vogel, 1992, Nathan and Smith, 1955, Petersen and Schubert, 2010, Lee *et al*, 2011 and Deng *et al*, 2012). The stimulation method/movement, from the heel up along the lateral plantar border and then medially across the transverse arch, was the same in all these studies. Yet the instrument used to elicit the reflex varied greatly. Instruments used included a small wooden stick (van Gijn, 1978, Lee *et al*, 2011 and Deng *et al*, 2012), a blunt steel probe

(Roby-Bramiet *al*, 1989), the sharp point at the back of a patellar hammer (Petersen and Schubert, 2010), a key (Nathan and Smith, 1955) or a pencil (Nathan and Smith, 1955). Despite varied modes of application of a mechanical stimulus, the method of elicitation of the reflex is not thought to be central to the diagnostic usefulness of this clinical test, instead the aspect key to the clinical utility of the elicitation of this reflex is the manner in which the resultant reflex response is interpreted (Kumar *et al*, 2000).

1.3.2. Interpretation of the Babinski reflex

It is important that, where ever possible, when interpreting a Babinski reflex response to not only look at the toes but to take into account reflex activity of the entire leg (Raijmakerset *al*, 1991, van Gijn, 1995 and Kumar *et al*, 2000). This is because the reflex is part of flexion synergy and as such involves more than just the toes (van Gijn, 1995). There are three important aspects of the reflex which should be observed when assessing the Babinski reflex (Raijmakerset *al*, 1991, van Gijn, 1995 and Kumar *et al*, 2000), which are:

- 1: Observation or palpitation of any contraction of the *extensor hallucislongus*. An extensor movement of the hallux is only pathological if it is accompanied by activity in this muscle.
- 2: Observation of contraction of other muscles in the leg. The response is only pathological if it involves simultaneous activity of all flexor muscles.
- 3: The response should be reproducible.

Raijmakerset *al* (1991) showed that with the use of these rules a decrease in observer variation when assessing the Babinski reflex is possible. However, despite the use of such guidelines, it is still difficult to interpret the Babinski response. The difficulty in correctly making use of observations of the Babinski sign to make clinical diagnoses could be due to

many factors such as voluntary toe movements, a very brisk flexion response (difficult to observe) that is then followed by the toes returning to their original position which could be mistaken for upward movement or flexing downwards movements of the other toes creating the illusion that the hallux extended upwards (van Gijn, 1976).

1.3.3. Rating of the reflex

An important aspect of clinical neurology is for medical professionals to be able to standardize their assessments of reflexes allowing better understanding between medical professionals, leading to more accurate diagnoses and improved treatments. Methods of recording and standardising the reflex magnitude of the Babinski reflex vary from subjective rating scales to EMG to (most recently) kinematics. All of these methods have different advantages and disadvantages and are discussed in this dissertation.

To date there is not one agreed, uniform subjective rating scale used to rate the Babinski reflex. The scales used in previously published studies range from a two point scale through to a five point scale. The two point scale options range from if the response is present or absent (Petersen and Schubert, 2010), flexor or extensor (Vogel, 1992, Nathan and Smith, 1955, Singerman and Lee, 2008) or up going or down going (Maher *et al*, 1992). The three point scales are as diverse as the two point scales and use the same options with the addition of an equivocal or inconclusive option (McCance *et al*, 1968, Vogel, 1992, Benz *et al*, 2005 and Cook *et al*, 2009). In the studies that used four point scales (Aydin, 2005, Deng *et al*, 2012 and Lee *et al*, 2011) or five point scales (van Gijn and Bonke, 1977, Estanol, 1983), though with similarities, no two scales were the same.

Many studies have studied the inter observer or inter-rater reliability of the Babinski reflex (McCance *et al*, 1968, Maher *et al*, 1992, Vogel, 1992, van Gijn, 1996b, van Gijn, 2002, Miller and Johnston, 2005, Singerman and Lee, 2008, Cook *et al*, 2009 and Lee *et al*, 2011).

These studies have reached widely differing conclusions that extend from recommending the reflex be taken out of the clinical neurological exam (Miller and Johnston, 2005) to almost perfect inter-rater reliability (Vogel, 1992). This is most likely due to the lack of standardization of the instrument/technique used to elicit the reflex, the scale used to assess the reflexor the expectation of the raters as to whether the sign should be positive or negative (van Gijn and Bonke, 1977).

Even though disagreement exists about whether the Babinski reflex can be interpreted and rated with low inter-rater reliability the usefulness of the Babinski sign as clinical tool remains to be viewed as one of the most important reflexes in clinical neurology and as such has many practical uses in both medicine and clinical research.

1.4. Practical uses of the Babinski response in medicine and clinical research

1.4.1. Medical diagnostic uses

In a clinical neurological setting it is very important to have an accurate diagnosis in order for suitable treatment to be provided (Cook *et al*, 2007). Misdiagnosis may result in further deterioration or use of the incorrect treatments. (Cook *et al*, 2007). The Babinski reflex is a useful diagnostic tool in many neurological screening tests.

For example the Babinski reflex is used as part of the assessment of the degree of spasticity (a common symptom of UMN syndrome) in stroke patients and spinal cord injury patients (Little *et al*, 1989, Somerfeld *et al*, 2004 and Benz *et al*, 2005). Spasticity presents with increased muscle tone, hyperreflexia with clonus and a release of flexor reflexes in the lower limbs (Adams and Hicks, 2005). As the Babinski response is a symptom of spasticity, the elicitation and grading of the Babinski reflex response is a useful tool in the assessment of severity of spasticity. In addition the Babinski reflex has been used to evaluate when a

patient is coming out of spinal shock (Koet *et al*, 1999). Spinal shock is the absence of reflexes and the presence of inert muscle activity seen directly following severe spinal cord injury or transection of the spinal cord (Koet *et al*, 1999, Brayet *et al*, 2005). The Babinski reflex has also been used to validate new assessment tools of spasticity (Benz *et al*, 2005).

The Babinski reflex may also indicate if there is a lesion along the spinal cord and aid in the localisation of that lesion (Hindfelt, 1976, Deng *et al*, 2012). Myelopathies, UMN lesion caused by narrowing of the spinal canal, can be detected with the use of the Babinski reflex (Cook *et al*, 2007, Cook *et al*, 2009 and Cook *et al*, 2011).

1.4.2. Clinical research uses

In medical research the Babinski reflex has been used in drug studies to test the efficiency of drug therapies (Milanov and Georgiev, 1994, Aydin, 2005). It has also been used to test the efficiency of novel interventions, such as transcutaneous electrical nerve stimulation, in the treatment of spasticity (Aydin, 2005). The improvement of the Babinski reflex, evaluated by the degree of movement of the toes and leg during the reflex was considered by Aydin (2005) to reflect improvements in spasticity. The insights offered by noting the presence/magnitude of the Babinski sign has therefore proved its usefulness in clinical research. However due to the intra and inter variability of the Babinski reflex the accuracy of using the Babinski reflex in drug studies is questionable. The historically subjective nature of the Babinski reflex and the large amount of inter-rater variations also questions the accuracy of this method.

1.5. Electromyography (EMG)

Electromyography is a technique used to measure the electrical activity produced by muscle activation (Robertson *et al*, 2004). There are two common methods used to record this muscle activity, surface EMG and needle EMG. Needle EMG is recorded by inserting needle

electrodes into the muscle being recorded (Robertson *et al*, 2004). Surface EMG is the more common method as it is non-invasive (Rainoldiet *al*, 2004). Surface EMG makes use of two surface electrodes placed over the body of the muscle and a third neutral grounding electrode (Robertson *et al*, 2004). However surface EMG of reflexes has been found to have a very low reproducibility in clinical settings (Stam and van Crevel, 1989) which could be caused by many factors such as the placement of the electrodes, the layers between the electrode and the muscle (e.g. subcutaneous fat) and influence of electrical activity in surrounding muscles (De Luca 1997).

Despite these factors surface EMG still has many clinical and research applications for neuromuscular assessments (Rainoldiet *al*, 2004). The amplitude of EMG recordings provides information on the activity in the muscle being recorded which makes it useful for reflex studies. Many studies, with EMG (both surface and needle EMG), have been performed on the Babinski reflex and were discussed in 1.2.5.

EMG recordings represent the muscle activation but not necessarily the subsequent movement generated by the muscle. Another objective method of assessing reflexes is kinematics. Kinematics is a method that accurately records the ensuing movement of a limb segment after the muscle activation and is discussed further in the following section.

1.6. Biomechanics (kinematics)

Even though objective recording of reflex responses have been made since Charcot in the late 1800's (as per Cartwright, 1992), it wasn't until the recent development of kinematics within the field of biomechanics that true objective measurements of movement could be made. Biomechanics is the study of the mechanics of living organisms. The division of biomechanics which is relevant to this review is kinematics. Kinematics looks at the motion of an object or segment in time and space (Kreighbaumet *al*, 1996). The way in which

kinematics of a movement are captured is through the use of high speed cameras and strategically positioned retro-reflective markers. The markers are placed on joints of a limb segment and through the use of specialized computer code a three dimensional model of the limb can be reconstructed. From this the degree of motion and the speed of movement can be calculated from the model. This provides an objective measure of movement of a specific limb or a combination of body segments.

Currently the only accepted objective measurement of reflexes is EMG of the muscles involved. Neurological examinations are mostly done subjectively by the physician reporting what he/she has seen and by the use of subjective rating scales. It is important to decrease any subjective variability found when assessing reflexes in order to create more accurate ratings of reflexes which will lead to more precise diagnoses and improved treatments. Biomechanics is ideal for the objective assessment of reflexes. Recently, biomechanical assessment has been used as a tool to objectively assess neurological reflexes however this is only in research studies and not yet in clinical practice. The withdrawal reflex has been looked at kinematically by Benz *et al* (2005). They assessed the changes in angles for the ankle, knee and hip (Benz *et al*, 2005). Other reflexes that have been looked at biomechanically include the patellar reflex (Tham *et al*, 2010, Dafkin *et al*, 2012 and Dafkin *et al*, 2013) and ankle clonus (Benz *et al*, 2005). To date the Babinski reflex has not been assessed with kinematics.

1.7. Rationale for the current studies

Spinal reflex testing is an important part of neurological examinations. The elicitation of the Babinski reflex is said to be one of the most important and clinically useful tools in neurology (Zafeiriou, 2004). There is a lack of recent studies focussing on the Babinski reflex with most studies having been conducted in the early half of the 20th century. With current

improvements in technology more aspects of the Babinski reflex can now be objectively assessed, however no research has yet been performed to objectively quantify the movement of the toes during this reflex (the long used indicator of pathology, ever since the reflex was first described) as well as the movement in the foot and leg. Such research may assist in elucidating factors which lead to difficulties experienced by physicians when implementing the Babinski sign as a diagnostic tool. Currently no standardised instrument is recommended to perform the reflex and there is no widely accepted reflex scale for reporting the outcomes of the reflex. Therefore assessing the technique used by neurologists performing the Babinski reflex test and the contribution of this technique to the resultant reflex magnitude may lead to a better understanding of what technique is needed to elicit the reflex. As the Babinski reflex is believed to be part of flexion synergy of the lower leg an assessment of what muscles are involved in the Babinski reflex and the resultant movement of the lower leg, as recorded kinematically, on patients with a known Babinski response compared to healthy controls may increase the current understanding of the complex relationship of the Babinski sign and flexion synergy. As no current standardised reflex scale is available for the Babinski reflex evaluating what aspects of the Babinski reflex are related to subjective evaluations of the Babinski reflex may aid in the development of an accepted reflex rating scale.

1.8. Aims

1. To evaluate the duration and applied pressures used by neurologists when testing the Babinski reflex as well as assessing the variation in these variables over five repetitions.
2. To investigate the relationship between the input variables of the reflex (the timing and pressures applied) with objective output variables namely the EMG activity of the *tibialis anterior* muscle and the degree of movement of the hallux in addition to the subjective measure of pain felt during the reflex test.
3. To objectively quantify the Babinski reflex both electromyographically and kinematically on patients with a positive Babinski sign and control participants. A comparison of these objective variables between these two groups will then be done.
4. To assess the inter-rater reliability of medical students and neurologists when rating a pre-recorded plantar response.
5. To determine what aspects of the reflex are most closely related to the ratings of the students and neurologists and if there is a difference between these groups in this regard.

Materials and Methods

Following the sequential nature of the hypotheses addressed in this dissertation, the description of data collection was separated into three phases. The first phase of the current dissertation aimed to assess the techniques used by neurologists performing the Babinski reflex test and additionally assessed whether the technique used followed conventional guidelines; and assessed what aspects of technique contributed to measures of reflex magnitude. Phase 2 aimed to objectively confirm the use of the Babinski sign as a tool for differentiating pathology from normal control reflexes (as well as quantifying any differences that might exist) by comparing objective measures of the Babinski reflex between patients with a positive Babinski sign and healthy controls. Phase 3 of this dissertation aimed to investigate the known large inter-rater variation in rating of the Babinski reflex by an assessment of how neurologists and medical students rate the reflex. The latter phase aimed to both quantify the variation within raters and between different types of raters as well as investigated what properties of the reflex, were related to the subjective evaluation of the Babinski sign by these groups. The laboratory design as well as the equipment used were the same for each phase and are discussed initially followed by the individual procedures for each phase.

2.1. Ethics

Ethical clearance for this study was obtained from the Human Research Ethics Committee (HREC) of the University of the Witwatersrand (M070452). All participants and patients voluntarily signed a written informed consent sheet (Appendix I) prior to participating in the study.

2.2. Equipment and setup

2.2.1. Laboratory design

The Babinski reflex is performed on patients in the supine position. To facilitate this a plinth was placed in the lab in a fixed position throughout the data collection period. Ten Optitrack(Natural Point, Oregon, USA) high speed cameras that record at 100 Hz were positioned around the plinth in an arrangement designed to optimize visibility of the leg and foot during the reflex. These cameras record data by tracking retro-reflective markers that were placed on the Babinski hammer and on specific anatomical landmarks of the foot and leg of participants. Before the start of each recording a dynamic and a static calibration was completed with the use of built in Optitrack Arena software to establish calibration constants for the kinematic system. Calibration was accepted only with a mean error below 0.15cm. Thewlis *et al*(2011) determined that the Optitrack cameras used in this study are as accurate as more widely used Vicon camera models.

2.2.2. Babinski hammer

A specialized custom built Babinski hammer was developed for this study. In order to closely resemble a hammer/foot scraper used during every day clinical examination(Figure 2.1A), while allowing for the measurement of the pressure that the hammer exerted on the foot to be recorded, a number of design aspects were incorporated. This was done by fixing a force transducer (Transducer Techniques, Temecula, California, model MLP-200 with a maximum capacity of 90.72kgs) to a pointed tip (1cm in length) made from the same material (nylon) as a clinical Babinski hammer. The force transducer had a length of 2.8cm and a width of 4.5cm. The hammer was 16cm in length with a diameter of 0.6cm.

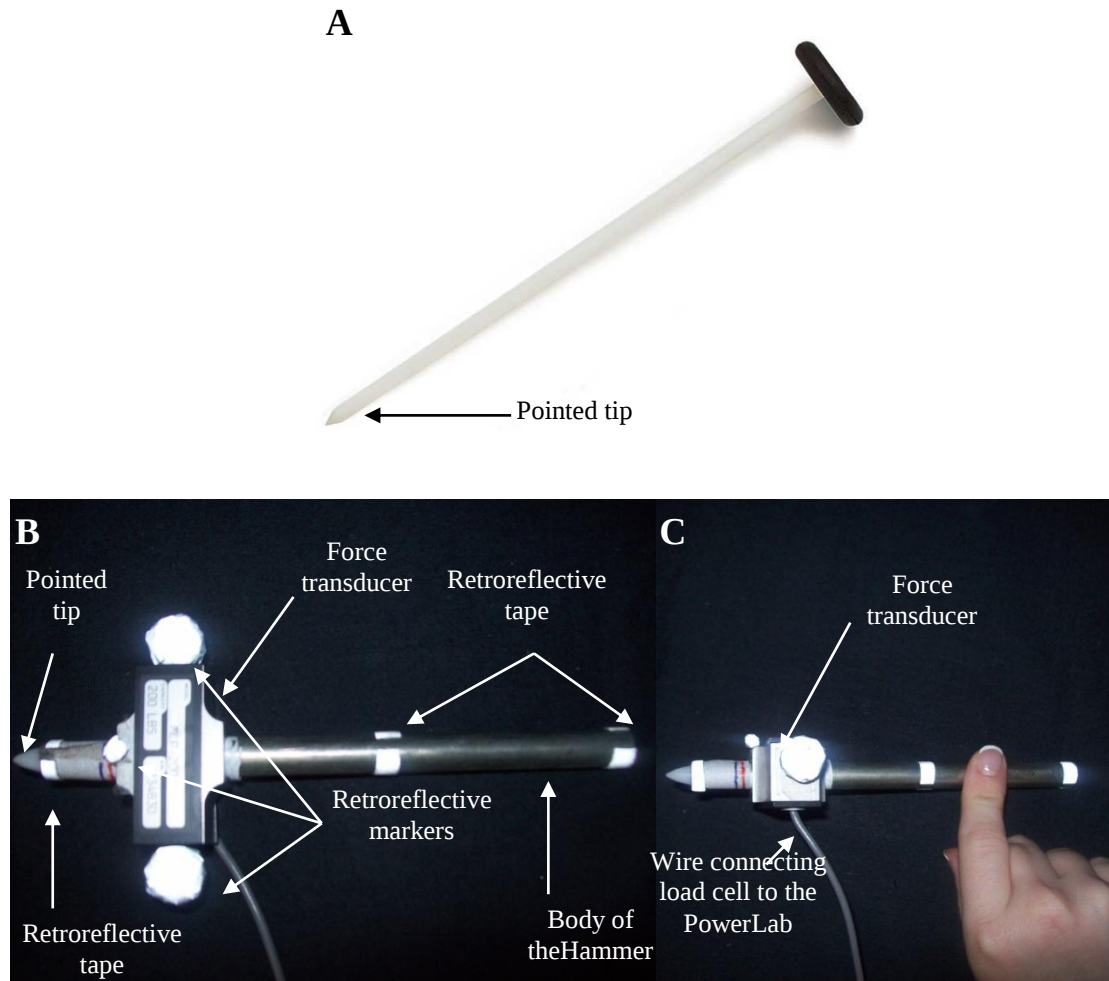


Figure 2.1:*A: Clinical Babinski hammer. The specialized Babinski hammer. B: Front view, C: Side view.*

The load cell was connected to a PowerLab (ADI instruments, 26T, Australia) which recorded the output of the pressure information. Before the start of each recording the Babinski hammer was calibrated by placing four weights of known mass onto the hammer and recording the voltages given. This allowed for the generation of a five point calibration curve (including unloading) (Appendix II) for the conversion of the voltages recording during the reflexes to grams and allowing for standardization between trials. In order for the position of the hammer to be tracked biomechanically three retro reflective markers as well as three strips of retro reflective tape were placed on the hammer. The markers were placed on either

side of the load cell as well as at the top of the load cell. The tape was placed just under the tip of the hammer, half way along the body and at the end of the handle, as seen in Figure 2.1B and C.

2.2.3. Participant biomechanical marker placement

The position of the retro-reflective markers on the participant's foot and leg were the same for all three phases of the current dissertation. Markers were positioned on the right or left leg and foot depending on which side the reflex was being elicited. Retro-reflective markers (diameter 1.8cm) were placed on the greater trochanter (hip), the medial and lateral epicondyles of the femur (knee) and on the lateral and medial malleoli (ankle). Markers were also placed midway between the ankle and knee markers and midway between the knee and hip markers (Figure 2.2). These markers enabled movement of the foot, ankle, lower leg, knee and upper leg segments to be accurately recorded.



Figure 2.2: Position of the retro-reflective markers on the leg.

Smaller retro reflective markers (diameter 0.3cm) were positioned on the foot in order to be easily differentiated as some of these markers were placed relatively close together. The

markers were positioned on the plantar surface of the body of the foot at the heel, the apex of the arch and on the tuberosity of the fifth metatarsal. Markers on the toes were placed at the head of the proximal phalanges as well as on the head of the distal phalanges on the first (hallux), third and fifth digits (Figure 2.3).



Figure 2.3: Placement of the retro-reflective markers on the plantar surface of the foot.

2.2.4. Electromyography

Electromyography of muscles in the legs of the participants was recorded with two surface electrodes positioned on the belly of each muscle (see figures 2.4 and 2.5). In Phase 1 only the *tibialis anterior* was assessed. Phase 2 assessed the muscle activity in *tibialis anterior*, *gastrocnemius* and *biceps femoris* in the ipsilateral leg as well as the *rectus femoris* in the contralateral leg. The muscles in the ipsilateral leg were selected as they are all involved in the shortening of the leg and are therefore important to the Babinski reflex which is part of flexion synergy and as such involves flexion in the entire leg (van Gijn, 1995). The *rectus femoris* of the contralateral leg was also examined as stimulation to the sole of the foot leads to a crossed extensor reflex response in the contralateral leg (Kugelberget al, 1960). The

reason that the *extensor hallucis longus* was not assessed in this dissertation is due to the need to use needle electrodes, which cause pain and could add artificial stimulation to the reflex (Landau and Clare, 1959), in order to accurately assess the *extensor hallucis longus*. The *tibialis anterior* was assessed as research has shown that in a pathological Babinski response the action potentials of the *extensor hallucis longus* and the *tibialis anterior* occur simultaneously (van Gijn, 1976). Phase 3 assessed the muscle activity in *tibialis anterior*, *gastrocnemius* and *biceps femoris*, such as in phase 2, the only difference being the exclusion of the *rectus femoris* in the contralateral leg.

2.3. Phase 1

The first phase of data collection was designed to assess how neurologists test the plantar reflex. For this phase both input and output variables of the reflex were recorded. The input variables that assessed the manner in which neurologists applied the mechanical stimulus to the plantar surface of the foot included: the maximum hammer pressure, average hammer pressure and duration of hammer stroke. The resultant recorded output variables of the reflex that emanated from both the subjective and objective responses of the participant subject were: the VAS score which measured the pain felt by the participant, the maximum amplitude of the *tibialis anterior* muscle activity and the change in hallux angle.

2.3.1. Participants

One participant's foot was used so that the size, skin thickness, elasticity and the friction of the hammer on the foot were standardized for every test. Twelve neurologists performed the reflex testing on the foot. Each neurologist did so on a different day to prevent habituation of the reflex response.

2.3.2. Procedure

The participant was placed in a supine position on the plinth. Retro reflective markers were placed on the right leg and foot (as described in 2.2.3 above). Muscle activity in the *tibialis anterior* muscle was recorded by placing two surface electrodes (diameter of 4.2cm) on the body of the muscle (Figure 2.4) and captured with the use of PowerLab (ADI instruments, 26T, Australia). A third grounding electrode was placed on the elbow of the participant.



Figure 2.4: Placement of the electrodes on lower leg to record muscle activity in the *tibialis anterior* muscle.

The neurologists were asked to perform the Babinski reflex testing, using the specialized Babinski hammer (described in 2.2.2), on the right foot of the participant as they would normally execute it in a clinical setting. Each neurologist performed the reflex testing five times. The participant was given a VAS scale (Appendix III) and asked to mark a point that accurately reflected his current level of pain related to the reflex testing after the performance of every test. The anchors of the VAS scale were no pain and most severe pain ever felt. Babinski reflex testing should not be painful. However I added a measure of pain to

assess whether clinicians do cause pain with the techniques they use to elicit the Babinski reflex. While the neurologists performed the reflex testing it was recorded kinematically with the use of the high speed cameras described in 2.2.1. The electromyographic activity in the *tibialis anterior* muscle was concurrently recorded.

2.4. Phase 2

The second phase of data collection tested responses in patients with a pathological Babinski reflex resulting from an upper motor neuron lesion, as diagnosed at the Charlotte Maxeke Johannesburg academic hospital. A group of healthy to age and gender matched normal controls were used as a comparator group. In order to test differences in attributes of reflexes of healthy controls and patients with UMN lesions, the following variables, describing the stimulus application and resulting characteristics of the reflex were quantified: the maximum hammer pressure, duration of hammer stroke, the average hammer pressure, the maximum amplitude of the four muscles measured, the change in hallux angle, the time taken to reach maximum hallux angle, the change in ankle angle, the time taken to reach maximum ankle angle and the movement latency.

2.4.1. Participants

Six patients with positive Babinski responses [displayed upward movement of the hallux when the lateral plantar foot surface was stroked with a clinical foot scraper] were recruited from the Charlotte Maxeke Johannesburg academic hospital. Six control participants were recruited from the University of the Witwatersrand medical school and were matched to the patients by age and gender. The age, gender, height and weight of each patient/participant was recorded and the knee width, ankle width, foot length and the width between the foot arch and the tuberosity of the fifth metatarsal was also measured.

2.4.2. Procedure

Each patient/participant lay supine on the plinth. The reflex was first elicited on both feet of the patients in order to see which side had a positive Babinski response. That leg was then selected as the reflex leg and the retro-reflective markers were placed on that leg and foot as described in 2.2.3. Muscle activity of the *tibialis anterior*, *gastrocnemius* and *biceps femoris* of the ipsilateral leg was recorded along with the *rectus femoris* in the contralateral leg with two surface electrodes over the body of each muscle (Figure 2.5). A grounding electrode was positioned on the patient/participants elbow. As in 2.3.2 the muscle activity from the electrodes was recorded, via clip on leads, with PowerLab (ADI instruments, 26T, Australia).

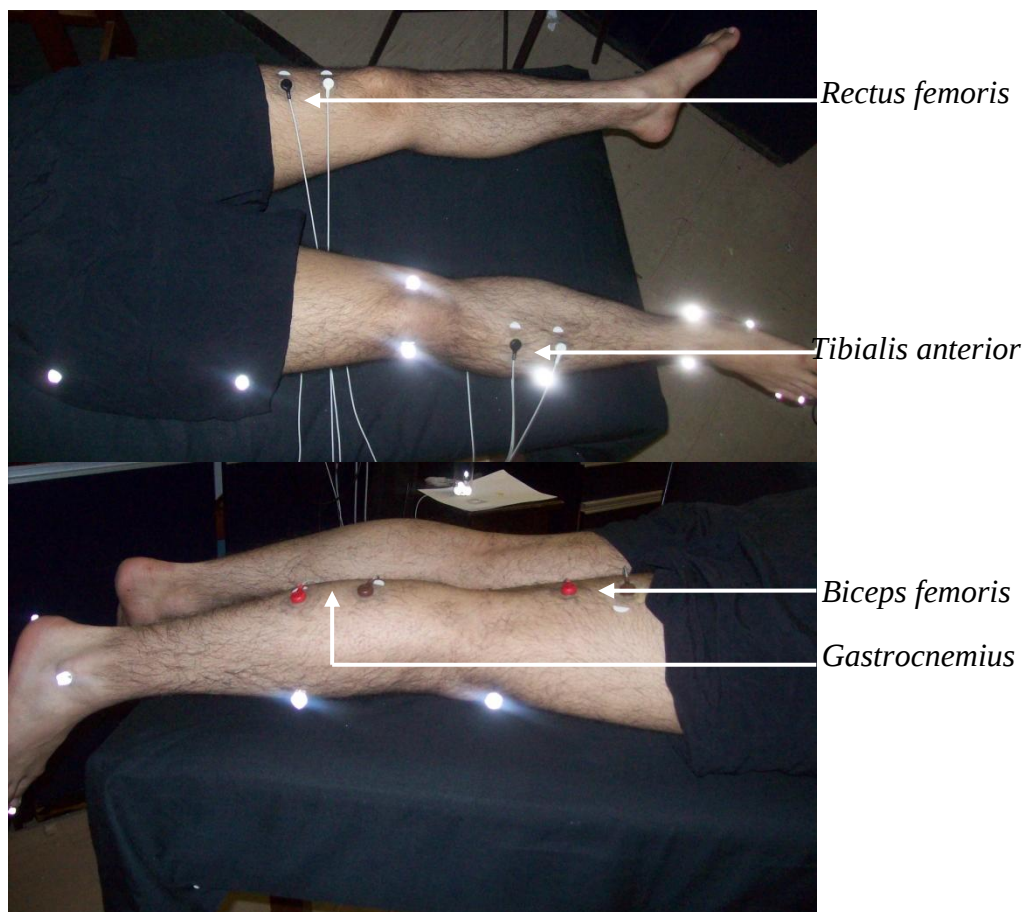


Figure 2.5: Position of the electrodes on the leg muscles for phase 2.

The upper quartile, median and lower quartile of the maximum pressure used by the 12 neurologists for each stroke of the hammer in phase 1 was calculated prior to the beginning of data collection for phase 2. In phase 2 it was attempted to obtain this previously measured clinical median application pressure when eliciting the reflex. The pressures used in phase 2 did vary slightly though as each individual responds differently (different sensitivities) and the pressure that elicited the best reflex was used.

Each patient/participant was stroked twice along the lateral plantar border curving towards the hallux on the selected reflex foot. The movement was recorded simultaneously, as previously described, via the high speed cameras and a conventional video camera (Sony, model DCR-HC21E, Japan) and concurrently with the recording of the EMG activity in the four selected muscles (described in section 2.4.2). The video footage from the conventional camera was used in phase 3.

2.5. Phase 3

Phase 3 assessed the inter-rater reliability of the Babinski reflex and what medical students and neurologists look for when diagnosing a pathological Babinski reflex. This phase assessed similar aspects of the leg movement and muscular activity as those used in phase 2 to assess the variables used to inform a diagnosis of a pathological Babinski reflex by different raters. The maximum amplitude of the *rectus femoris* was however excluded as it was recorded on the contralateral leg which could not be seen in the videos.

2.5.1. Raters

Twelve fourth year medical students and 12 neurologists assessed 15 videos of the Babinski reflex.

2.5.2. Procedure

Video footage of the Babinski reflex was recorded as described in 2.4.2. The footage for 15 reflexes was randomized and shown to the 12 medical students and 12 neurologists who were instructed to rate the reflexes as either pathological or non-pathological (Appendix IV).

2.6. Analysis

For each of the three phases the hammer, kinematic and electromyographical analysis was the same so it will collectively be described below. The VAS scale was analysed by measuring the distance of the line marked by the participant from the first anchor (mm).

2.6.1. Babinski Hammer analysis

The variables taken from the Babinski hammer data captured by the PowerLab were maximum pressure (kg), average pressure (kg) and the duration of the stroke along the foot (s) (Figure 2.6). The average pressure was taken as an average of the pressure exerted by the hammer on the foot from the start point to the end point (Figure 2.6.). All pressures were recorded in volts (V) and then converted to kilograms (kg) as per the previously described calibration.

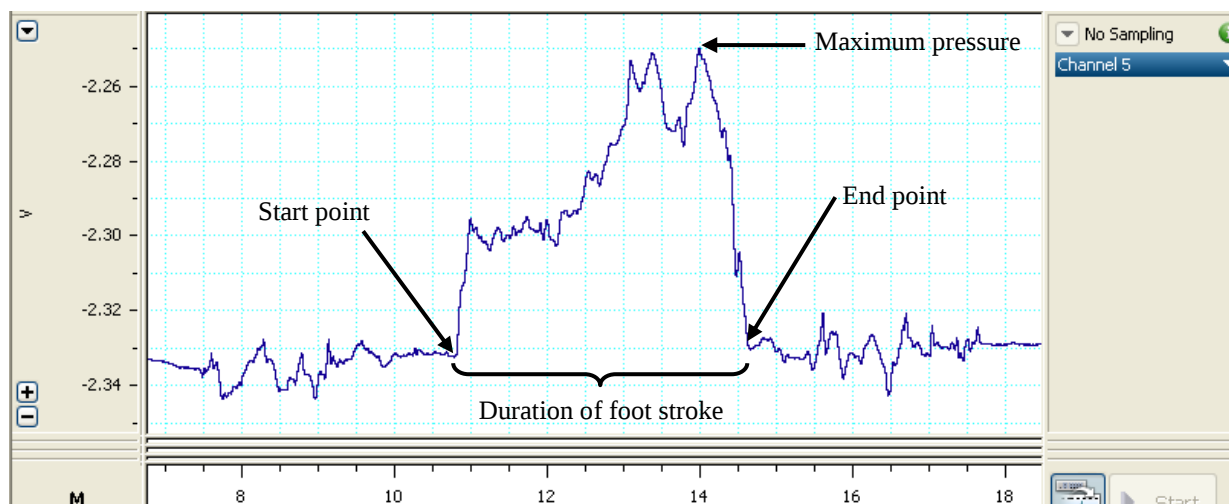


Figure 2.6: A Trace of the Babinski hammer data for one stroke of the foot taken from the PowerLab.

2.6.2. Electromyographical analysis

The electromyographical data used in this study was the maximum amplitude (mV) for each of the muscles recorded. With the Babinski reflex when stimulation of the skin stops so does the reflex response (van Gijn, 2003). Thus the reflex occurred only when the hammer was stroking the foot and therefore was reflected by the trace created by the hammer. To avoid including additional movement after the reflex due to foot relaxation, the duration of the hammer trace was used as a guide for the duration of the muscle activity during the reflex. The maximum and minimum values on the electromyographical trace for each muscle, for the duration of the hammer, were recorded. The maximum amplitude was then calculated by taking the difference between the maximum and the minimum values.

2.6.3. Kinematic analysis

The kinematic variables used for phase 1 were the angle of the hammer to the foot (see section 2.6.3.1) and the change in hallux angle during the reflex (see section 2.6.3.1). The kinematic variables used for phase 2 and phase 3 were change in hallux angle, time to

maximum hallux angle, change in ankle angle and time to maximum ankle angle (see section 2.6.3.1). Movement latency was also used in phases 2 and 3 and was calculated as the time taken between the beginning of the hammer stroke and initiation of the movement of the hallux.

All image processing and subsequent kinematic data handling were conducted with 3D Motion Kinematic and Kinetic Analyser (Mokka version 0.5.1) and Matlab7 (Mathworks, Natick, USA). 3D Motion Kinematic and Kinetic Analyser was used to label the position of the markers (Figure 2.7) which was then exported to Matlab7 where the angles were obtained by custom algorithms [written by me and my colleagues, as shown in Appendix V (contributions of other code writers is detailed in the contributions section at the beginning of this dissertation)].

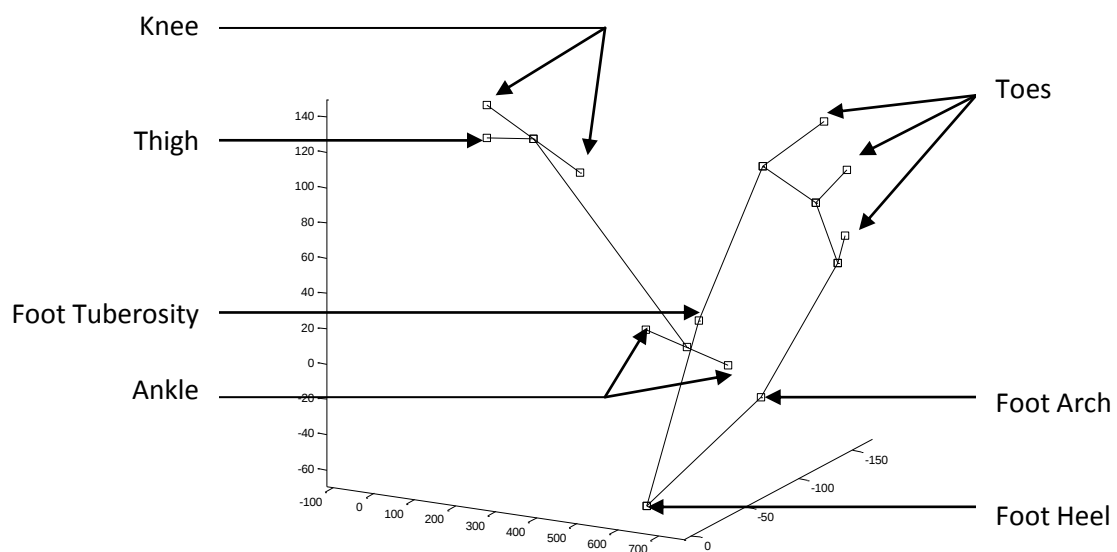


Figure 2.7: A three dimensional reconstruction of the foot, used for MatLab7 based analysis (axes are in cm relative to an arbitrary reference point).

2.6.3.1. Hammer angle

The angle of the hammer was calculated at two points along the foot for each stroke. The first point was when the hammer was placed against the foot (start of the stroke) and the second

was when the hammer was midway along the foot (between the arch and tuberosity markers). The hammer angle was calculated as an angle between the foot plane (created between the bottom of the hallux, the foot heel and the bottom of the little toe markers) and the hammer vector (created from any two points along the hammer longitudinal axis).

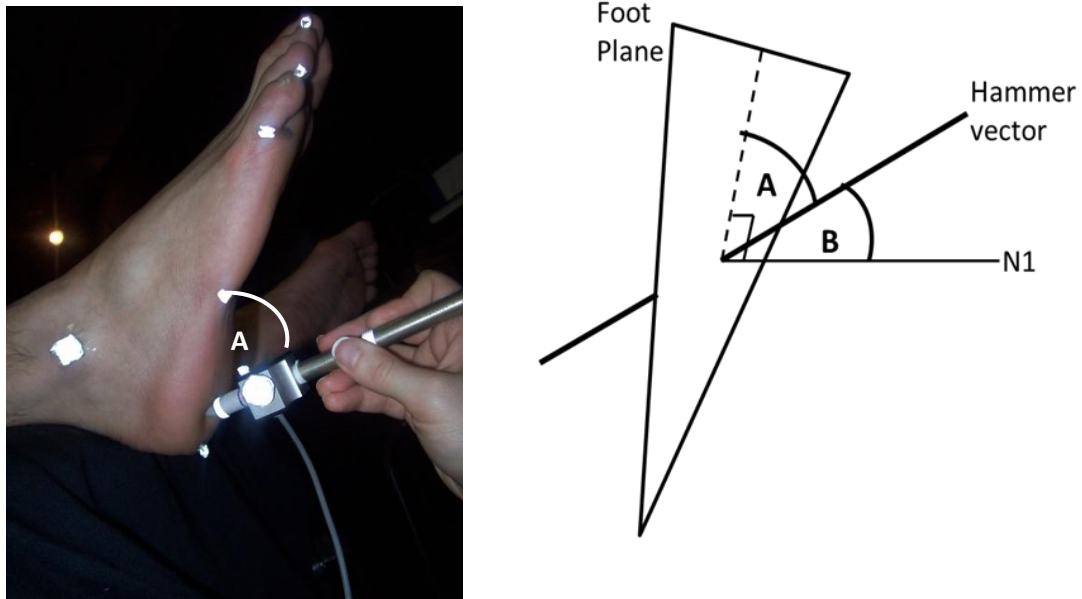


Figure 2.8: *The angle between the hammer vector and the foot plane (angle A). In order to obtain this angle a normal (N1) was created perpendicular to the foot plane and the angle between this normal and the hammer vector (angle B) was calculated using $\arccos B$. Therefore the angle A is equal to $90^\circ - \arccos B$.*

2.6.3.2. Hallux angle

The hallux angle was calculated as the angle between the arch plane (created between the bottom of the hallux, the foot arch and the bottom of the little toe markers) and the hallux vector (bottom of hallux to the top of hallux).

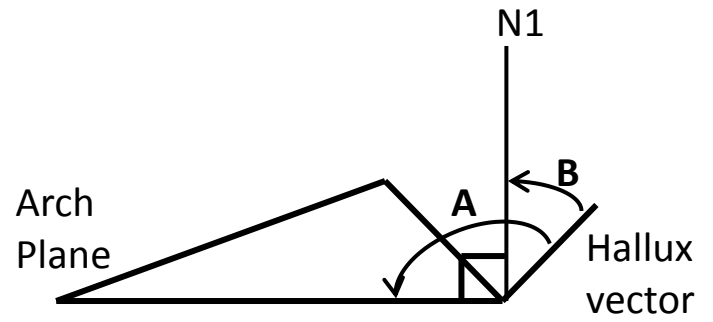
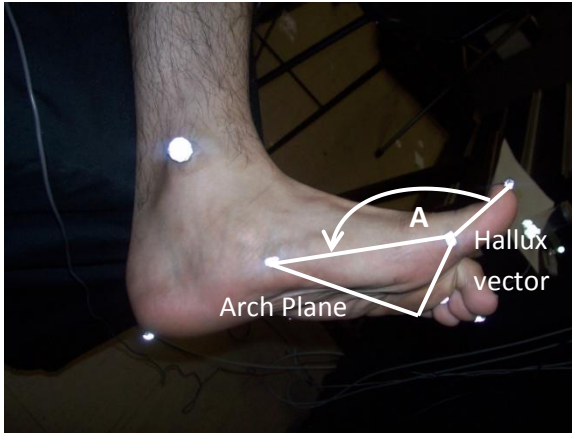


Figure 2.9: The angle between the hallux vector and the arch plane (angle A). A normal (N1) was created perpendicular to the arch plane. The angle between the hallux vector and N1 (angle B) equals $\arccos B$. Angle A therefore equals $90^\circ + \arccos B$.

Hallux angle was calculated for the duration of the hammer stroke for every reflex. This allowed the starting angle, maximum angle and the time to maximum angle variables to be obtained. The change in hallux angle could then be calculated (from the initial point to the maximum angle).

2.3.6.3. Ankle angle

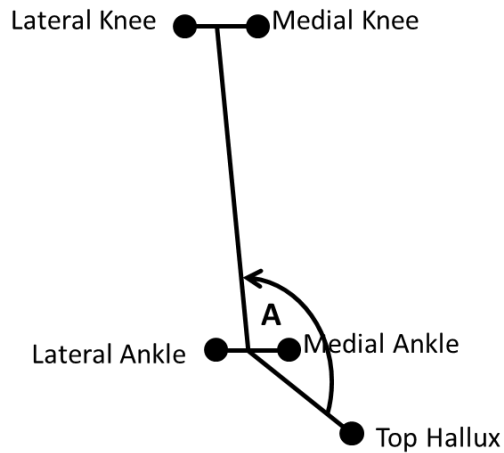


Figure 2.10: *The ankle angle (A) was calculated as the angle between the calf vector (midpoint of the knee markers to midpoint of the ankle markers) and the foot vector (top hallux marker to the midpoint of the ankle markers).*

The ankle angle was calculated for the duration of the hammer stroke (the same as the hallux angle 2.3.6.2.) so that the change in ankle angle (from the initial point to the maximum angle) and the time to maximum ankle angle could be obtained.

2.7. Statistics

All statistical analysis was performed with GraphPad Prism (Version 5.00 for Windows, GraphPad Software, San Diego California USA). Statistical significance was set at $p < 0.05$.

2.7.1. Phase 1

All the data in phase 1 were shown to be non-parametric and as such are expressed as median and interquartile range unless specified otherwise.

The intra-variation for each variable describing the hammer use by each neurologist was assessed with the coefficient of variance for the five strokes. The inter-variation of the

neurologists was assessed with the coefficient of variance for the means of all the neurologist's strokes. Low variance was classed as a variance of below 10%. This procedure was performed for the inputs to the reflex (maximum hammer pressure, average hammer pressure and the duration of the hammer stroke).

The inputs were then tested for a correlation to the maximum amplitude of the *tibialis anterior*, the change in hallux angle and the VAS score by means of Spearman's rank correlations. All strokes of the foot were treated as individual occurrences for this part of phase 1 because the hypothesis at this point was not to assess the skill of different neurologists; rather it was to see if variations in the nature of stimulus application caused alterations in the response.

2.7.2. Phase 2

All the data in phase 2 are parametric and expressed as mean $\pm$ SD apart from: change in ankle angle, time to maximum ankle angle and maximum amplitude of *tibialis anterior* and *gastrocnemius* which are non-parametric and hence expressed as median and interquartile range.

The height, weight, BMI, age, knee width, ankle width, foot width and foot length of the patients and controls were compared by means of unpaired student's t-tests as well as the maximum and average hammer pressure and the duration of hammer stroke. This was done in order to determine if the input variables were the same during the elicitation of the reflex on the patients and controls. Change in hallux angle, time to maximum hallux angle, reflex latency, maximum amplitude of *biceps femoris* and maximum amplitude of *rectus femoris* were compared for patients and controls by means of unpaired student's t-tests. Change in ankle angle, time to maximum ankle angle and maximum amplitude of *tibialis anterior* and maximum amplitude of *gastrocnemius* were compared for patients and

controls by means of Mann Whitney tests due to the non-parametric nature of the data. T-test results are expressed as t (degrees of freedom) and Mann Whitney test results are expressed as U. If a significant difference was found between any of the variables of the patients versus the controls it was taken that that variable differed in presentation in a healthy response and a positive Babinski sign.

2.7.3. Phase 3

The data in phase 3 are parametric and expressed as mean $\pm$ SD with the exception of maximum amplitude of *tibialis anterior* and *gastrocnemius*, which are non-parametric (expressed as median and interquartile range).

The inter-rater reliability was assessed by means of the kappa statistic (Landis and Koch, 1977) with a kappa value of 1 signifying almost perfect agreement between the raters and a kappa value of 0 signifying very poor agreement.

The raters assessed all 15 videos (combined patients and controls). Separate means were calculated for the reflexes that were rated as pathological and the reflexes rated as non-pathological for each variable of the reflex for each rater. These means were then grouped as students pathological, students non-pathological, neurologists pathological and neurologists non-pathological for each variable and ANOVAs followed by Bonferroni's post hoc tests (or Kruskal-Wallis ANOVA with a Dunn's post hoc test) were used to assess the differences between the groups. If a difference was found unpaired t-tests or Mann Whitney U-tests were performed. If a significant difference was found between either students pathological and students non-pathological or between neurologists pathological and neurologists non-pathological the relevant variable was considered to be used by the raters to assess the reflex.

Results

Due to the multi-phase structure of the study in the current dissertation, the results section has been separated into the three phases. The results for phase 1 begin with a description of the participant followed by the variation found for the input variables (maximum and average hammer pressure and the duration of the hammer stroke) for the 12 neurologists. Lastly the relationship between the variables describing the application of the stimulus to the foot of the participant and the resulting pain, muscle activity and toe movements is shown. Phase 2 starts with the patient's and matched control's demographics and the hammer stimuli applied to all subjects. This is subsequently followed by the relationship between the measured variables of the Babinski reflex for the patients and controls. Phase 3 also begins with a description of the participants and the hammer stimuli applied to all subjects. Inter-rater reliability and the characteristics used to diagnosis a reflex are then shown.

3.1. Phase 1

3.1.1. Participant description

One healthy 24 year old male participant (height 1.73m, weight 75kg) was used in phase 1. The participant had a foot length (measured from the heel to the top of the middle toe) of 23cm and a foot width (measured from the tuberosity of the fifth metatarsal to the apex of the arch) of 9cm and no neurological abnormalities.

3.1.2. Input variances

Even with the instruction to all neurologists to use the techniques used for their everyday clinical methods, eight of the neurologists (neurologists 1, 4, 5, 7, 8, 9, 10 and 12) performed the reflex by running the hammer along the lateral plantar border of the foot and curving in towards the hallux. The other four (neurologists 2, 3, 6 and 11) ran the hammer up the centre of the foot, from the heel to the bottom of the middle toe.

The median, first and third quartile and the range of values for the neurologists for the output variables are shown in table 3.1.

Table 3.1: Median, first and third quartile and range of values for the neurologists (n=12) for maximum hammer pressure, average hammer pressure and duration of hammer stroke.

	Median	First Quartile	Third Quartile	Range
Maximum Hammer Pressure (grams)	426.8	312.4	561.0	182.6-1285.0
Average Hammer Pressure (grams)	290.8	205.7	396.3	90.8-709.1
Duration of Hammer Stroke (s)	2.0	1.5	3.9	1-9.3

The intra-variability and the inter-variability of the neurologists for maximum hammer pressure, average hammer pressure and duration of hammer stroke are shown in table 3.2.

Table 3.2: The coefficient of variance for each neurologist for five strokes (intra-variability) and for the 12 neurologists combined (inter-variability) for the input variables of the reflex.

Neurologist	Maximum Hammer Pressure (%)	Average Hammer Pressure (%)	Duration of Hammer stroke (%)
1	17.5	10.4	6.9*
2	11.2	12.2	13.1
3	13.5	11.0	9.8*
4	22.0	14.8	13.1
5	23.4	27.6	10.0*
6	4.3*	1.9*	8.4*
7	22.3	14.8	41.3
8	39.7	26.1	16.1
9	8.4*	15.0	10.7
10	14.3	11.8	3.6*
11	14.1	21.4	12.3
12	16.6	20.0	8.8*
Combined	47.5	44.2	66.9

* Low variability

3.1.3. The relationship between variables describing the application of the stimulus to the foot and the resulting pain, muscle activity and toe movements

No significant correlation was found between the maximum amplitude of the *tibialis anterior* muscle activity and maximum ($R^2 = 0.06$, $p > 0.05$) and average ($R^2 = 0.02$, $p > 0.05$) hammer pressure or duration of hammer stroke ($R^2 = 0.06$, $p > 0.05$). The duration of the hammer stroke was also not significantly correlated to the VAS score (Figure 3.1C). There were significant positive correlations between the VAS score and the maximum (Figure 3.1A) and average hammer pressures (Figure 3.1B) as well as between all the input variables and the change in hallux angle (Figure 3.2).

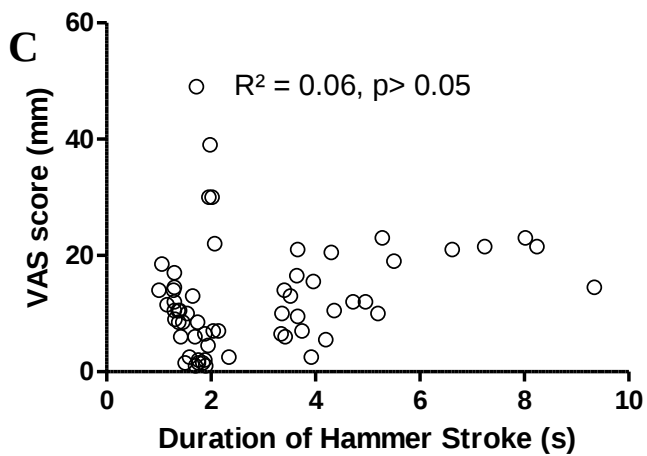
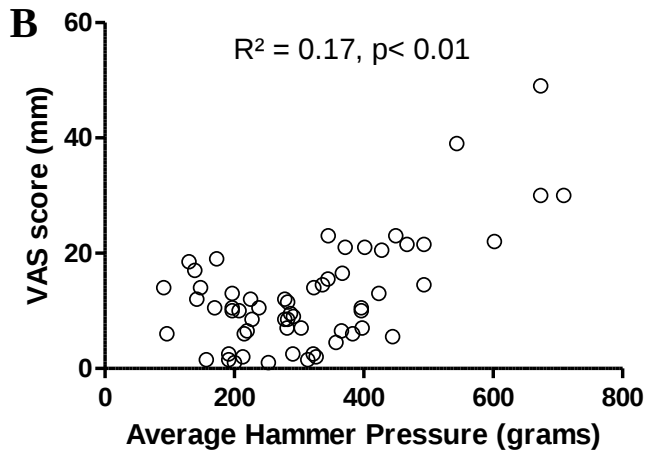
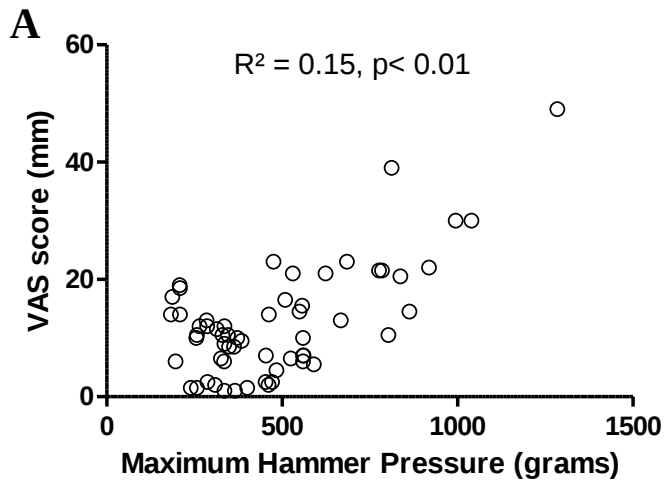


Figure 3.1: Spearman's correlations between maximum (A) and average (B) hammer pressure and duration of hammer stroke (C) and the resulting pain experienced (VAS score).

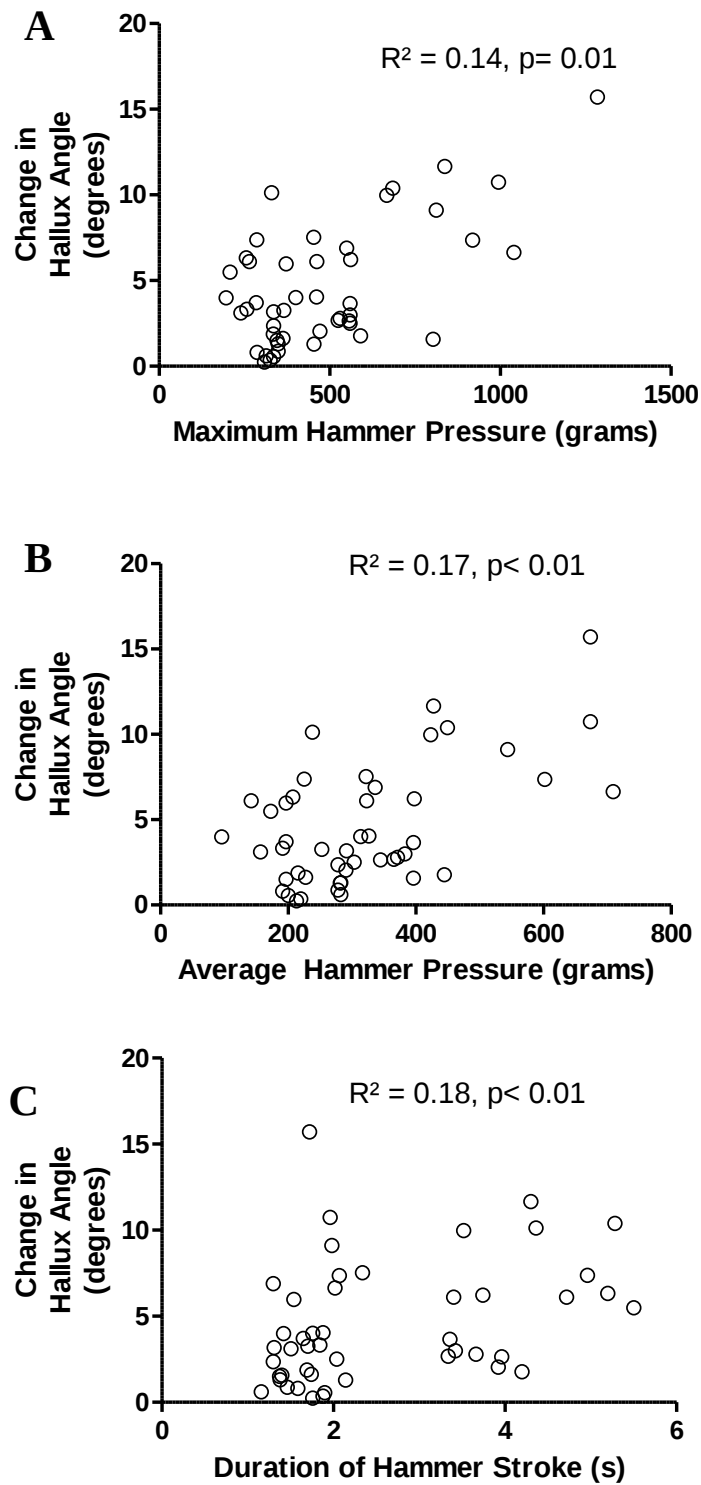


Figure 3.2: Spearman's correlations between the change in hallux angle and the maximum hammer pressure (A), average hammer pressure (B) and duration of hammer stroke (C).

3.2. Phase 2

Features of the reflexes that were compared were both kinematic and electromyographic objective variables as well as the movement latency. The kinematic variables were: the change in hallux angle, the time taken to maximum hallux angle, the change in ankle angle and the time taken to maximum ankle angle. The change in hallux angle represents the degree of movement of the hallux. The time taken to maximum hallux angle assessed how long the hallux took to reach its maximum angle and thus the speed of its movement. Similarly the change in ankle angle represents the degree of movement of the angle between the ankle and the foot while time taken to maximum ankle angle assessed the speed at which the foot moved.

The electromyographic variables that were investigated in phase 2 included: the maximum amplitude of the *tibialis anterior*, *gastrocnemius* and *biceps femoris* of the ipsilateral leg. All of these muscles are involved in the shortening of the leg and are therefore important to the Babinski reflex (van Gijn, 1995). The *tibialis anterior* flexes the foot upwards (dorsiflexion), the *gastrocnemius* crosses the posterior knee joint and flexes the knee when the foot is dorsiflexed and the *biceps femoris* aids in knee flexion (Marieb and Hoehn, 2010). The maximum amplitude of the *rectus femoris* of the contralateral leg was also examined as stimulation of the sole of the foot leads to a crossed reflex response in the contralateral leg (Kugelberget *al*, 1960). This response is seen most prominently in the proximal muscles (Kugelberget *al*, 1960) and as such the *rectus femoris* was examined due to its proximal position. Furthermore the *rectus femoris* is an extensor of the lower leg working by extending the knee (Marieb and Hoehn, 2010). The crossed reflex response seen in the contralateral leg has been hypothesized to aid the maintenance of balance (Kugelberget *al*, 1960) and as such the response is likely to be extensor. The effector of the pathological response is the *extensor hallucis longus* (van Gijn, 1975). Unfortunately, in the current study, the electrical activity of

this muscle was not investigated because it is a deep set muscle and cannot be recorded with surface electrodes. The use of needle electrodes was avoided as they may cause pain to the participant and could alter the reflex response. The movement latency was the time taken between the application of the stimulus and the initiation of visible movement of the hallux. The movement latency represents the speed of the reflex response.

3.2.1. Participant demographics

The characteristics of the patients and the age matched controls are shown in table 3.3. The reasons for the positive Babinski reflex in the six patients included: stroke (n=3) (one patient suffered a stroke five years ago, one 15 months before data collection and one had had a second stroke 15 months prior to data collection, their first 12 years ago), T8 myelopathy (n=1) (diagnosed within a week of data collection), cervical damage due to an accident that occurred 18 months ago (n=1) and suspected motor neuron disease (n=1).

Table 3.3: Characteristics of the patients and controls (means $\pm$ SD).

	Patients (n=6)	Controls (n=6)
Height (m)	1.7 $\pm$ 0.1	1.7 $\pm$ 0.1
Weight (kg)	65.3 $\pm$ 4.3	85.2 $\pm$ 13.4
BMI (kg/ m ²)	23.5 $\pm$ 3.8	29.7 $\pm$ 2.6
Age (years)	43.8 $\pm$ 9.0	44 $\pm$ 9.9
Gender (M/F)	4/2	4/2
Knee width (cm)	8.0 $\pm$ 0.9	8.5 $\pm$ 1.2
Ankle width (cm)	7.1 $\pm$ 0.5	7.0 $\pm$ 0.5
Foot width (cm)	7.1 $\pm$ 0.5	6.5 $\pm$ 1.1
Foot length (cm)	21.8 $\pm$ 2.0	23.3 $\pm$ 1.8

There were no significant differences between the characteristics for the patients and controls except for weight ($t_{10} = 3.44$, $p < 0.01$) and body mass index (BMI) ($t_{10} = 3.31$, $p < 0.01$).

3.2.2. Hammer inputs

There was no significant difference between the maximum and average hammer pressures exerted on the patients (Median: 494.5kg, Interquartile (IQ) ranges: 365.8kg, 532.0kg; Median: 325.7kg, IQ ranges: 205.9kg, 388.9kg) and on the controls (Median: 381.7kg, IQ ranges: 321.0kg, 436.9kg; Median: 230.4kg, IQ ranges: 209.9kg, 289.9kg) ($t_{22} = 1.84$, $p = 0.08$ and $t_{22} = 1.62$, $p = 0.12$). There was however a significant difference in the duration of hammer stroke between the patients and controls ($t_{22} = 2.41$, $p = 0.02$) with a longer stroke time used on the controls ($3.0 \pm 0.8s$) than the patients ($2.5 \pm 0.7s$).

3.2.3. Relationship between the measured variables of the Babinski reflex for the patients and controls

Change in hallux angle, time to maximum hallux angle, change in ankle angle and time to maximum ankle angle could not be measured for both strokes of some of the patients and controls due to missing markers in the captured kinematic data (it was not desirable to optimise data collection quality in these patients, since doing so would have caused greater levels of patient discomfort). However there was at least one measurement for every patient/control for each variable. Two of the patients were missing values for movement latency as there was no visible movement of the toes for those strokes.

There was a significant difference in the change in hallux angle (Figure 3.3) between patients and controls, with patients showing more dorsiflexion, but not with the absolute change in hallux angle ($t_{19} = 1.76$, $p = 0.09$). No significant difference was found between patients and controls for time to maximum hallux angle ($t_{19} = 1.31$, $p = 0.21$).

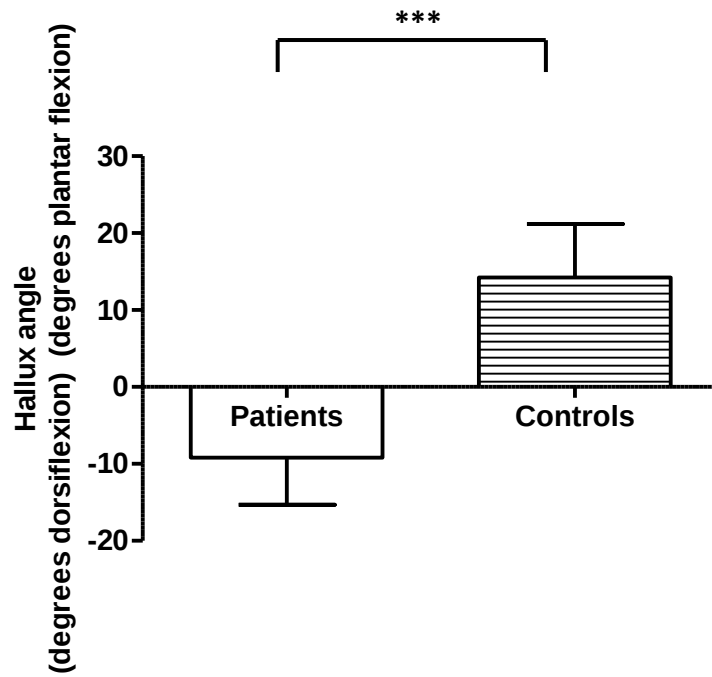


Figure 3.3: Unpaired t-test between patients and controls for change in hallux angle. ***

$t_{19} = 8.16, p < 0.0001$.

No significant difference was found between the patients and controls for change in ankle angle ($U=24, p = 0.56$) and time to maximum ankle angle ($U=15.50, p = 0.13$).

Movement latency between the patients and controls was found to be significantly less in patients (Figure 3.4).

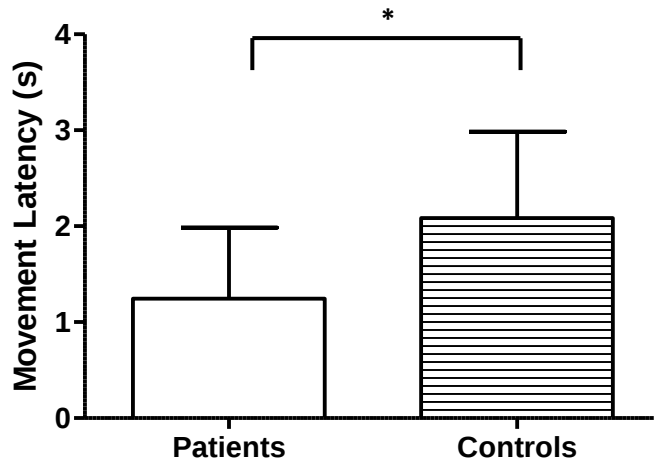


Figure 3.4: Unpaired *t*-test between patients and controls for movement latency. * $t_{20} = 2.37$, $p = 0.03$.

The maximum EMG amplitudes for the *gastrocnemius*, *biceps femoris* and *rectus femoris* were not significantly different between the patients and controls ($U = 53$, $p = 0.29$; $t_{22} = 0.08$, $p = 0.94$ and $t_{22} = 1$, $p = 0.33$). The maximum EMG amplitude for the *tibialis anterior* was significantly different between the patients and controls (patients displaying less muscle activity, Figure 3.5).

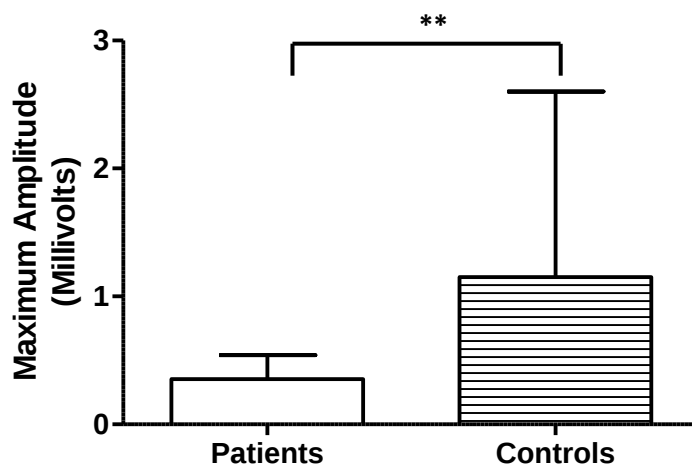


Figure 3.5: Mann Whitney *U*-test between patients and controls for maximum EMG amplitude of the *tibialis anterior* muscle. ** $U = 22$, $p < 0.01$.

3.3. Phase 3

3.3.1. Participant demographics

The participants whose reflexes were recorded are described in table 3.4. The five participants with a positive Babinski response were five of the patients included in phase 2 and as such have the same pathologies. The characteristics of the raters are shown in table 3.5.

Table 3.4: Characteristics of the participants whose reflexes were recorded (n=10).

	Mean $\pm$ SD	Range
Height (m)	1.7 $\pm$ 0.1	1.5 – 1.8
Weight (kg)	75 $\pm$ 16.6	50 - 105
BMI (kg/m ²)	26.6 $\pm$ 3.7	22.3 – 34.3
Age (years)	37.3 $\pm$ 12.9	21 - 61
Gender (M/F)	10/5	
Knee Width (cm)	8.4 $\pm$ 0.9	6.7 - 10
Ankle Width (cm)	7.6 $\pm$ 0.9	6.2 - 10
Foot Width (cm)	7.4 $\pm$ 1.0	6 - 9
Foot Length (cm)	22.6 $\pm$ 1.9	19 – 25.5

Table 3.5: Characteristics of the raters (mean $\pm$ SD).

	Neurologists (n=12)	Medical Students (n=12)
Age (years)	33.3 $\pm$ 6.6	24.3 $\pm$ 3.0
Gender (M/F)	6/6	4/8
Year of study	NA	4 $\pm$ 0
Years as a doctor	8.6 $\pm$ 5.8	NA

3.3.2. Variables describing the application of the stimulus to the foot of the participants

The mean maximum hammer pressure for the 15 reflexes was 439.9 ± 165.3 grams with a range of 296.8-928.0 grams. The mean hammer pressure was 268.5 ± 75.3 grams with a range of 154.4–404.5 grams and the mean duration of the hammer stroke was 3.0 ± 0.7 s with a range of 2.2-4.3s.

3.3.3. Inter-rater reliability

The kappa values for neurologists and students agreements were 0.72 and 0.67 respectively showing substantial rater agreement for both groups (Landis and Koch, 1977). The overall kappa value for the combined group of students and neurologists was 0.70. This also showed that there was substantial rater agreement between the ratings of all raters combined (Landis and Koch, 1977).

3.3.4. Diagnostic characteristics

There were significant differences for almost all of the variables used to describe kinematic and electromyographic aspects of a reflex when compared between what raters had judged to be pathological and non-pathological reflexes (Figures 3.6, 3.7, 3.8 and 3.9). Both neurologists and students classed pathological reflexes as having hallux dorsiflexion (Figure 3.6 A), brisker foot movement (Figure 3.7 B), smaller movement latency (Figure 3.8) and more activity in the *gastrocnemius* muscle (Figure 3.9 A) compared with non-pathological reflexes. Neurologists alone also associated brisker hallux movement (Figure 3.6 B) and a lesser degree of foot dorsiflexion (Figure 3.7 A) with pathological reflexes. Students alone associated more muscle activity in *biceps femoris* (Figure 3.9 B) with pathological reflexes. The exception to the latter variables, which showed differences between what was rated as pathological or non-pathological was the maximum amplitude of the *tibialis*

anteriormuscle. For the latter variable no significance difference was found between students rating of pathological and non-pathological or between neurologists rating of pathological and non-pathological.

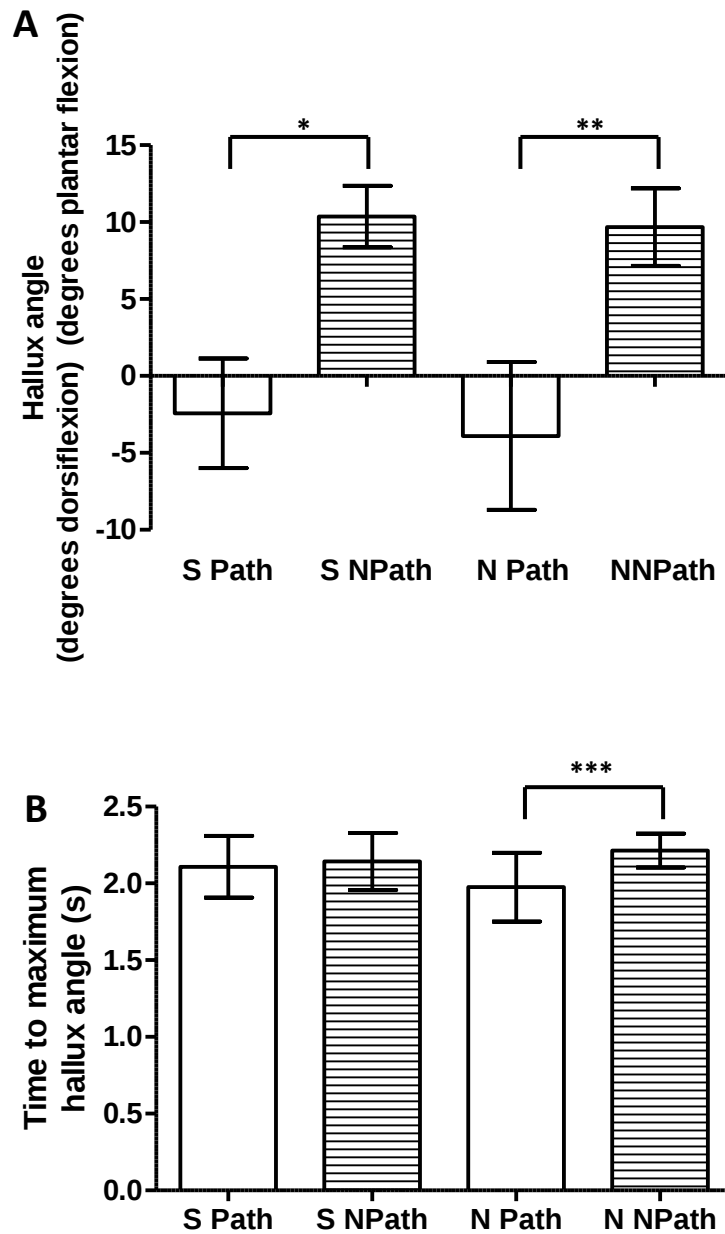


Figure 3.6: One-way ANOVAs run on change in hallux angle (A) and time taken to reach maximum hallux angle (B) for the reflexes rated pathological by medical students and neurologists and the reflexes rated non-pathological by medical students and neurologists. S Path= students pathological, S NPath= students non-pathological, N Path= neurologists pathological, N NPath= neurologists non-pathological. * $t_{22}=10.84$, $p<0.0001$; ** $t_{22}=8.68$, $p<0.0001$; * $t_{22}=3.30$, $p<0.01$.**

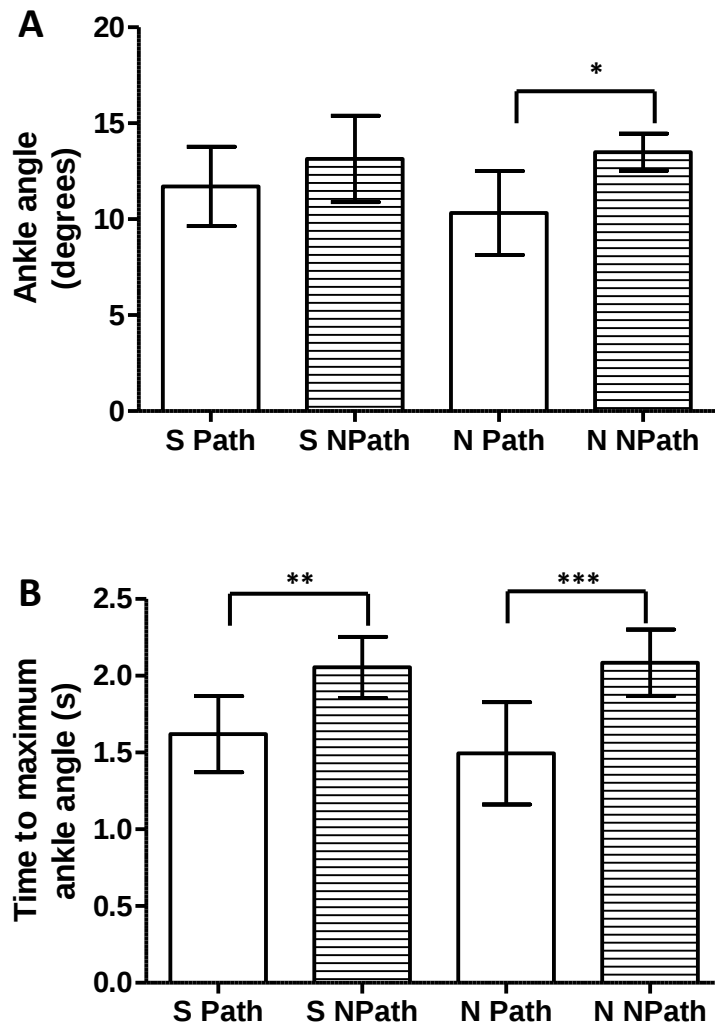


Figure 3.7: One-way ANOVAs run on change in ankle angle (A) and time taken to reach maximum ankle angle (B). S Path= students pathological, S NPath= students non-pathological, N Path= neurologists pathological, N NPath= neurologists non-pathological.

*** $t_{22}=4.58$; $p=0.0001$; ** $t_{22}=4.75$; $p<0.0001$; *** $t_{22}=5.14$, $p<0.0001$.**

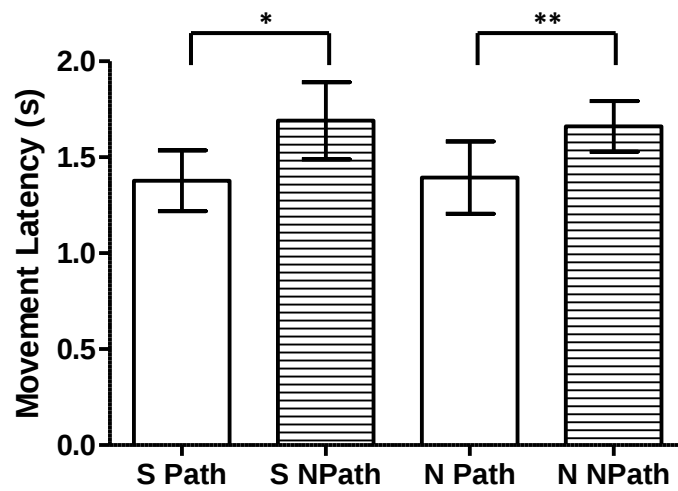


Figure 3.8: One-way ANOVAs run on movement latency. S Path= students pathological, S NPath= students non-pathological, N Path= neurologists pathological, N NPath= neurologists non-pathological. $t_{22}=4.24$, $p<0.001$; ** $t_{22}=4.03$; $p<0.001$.*

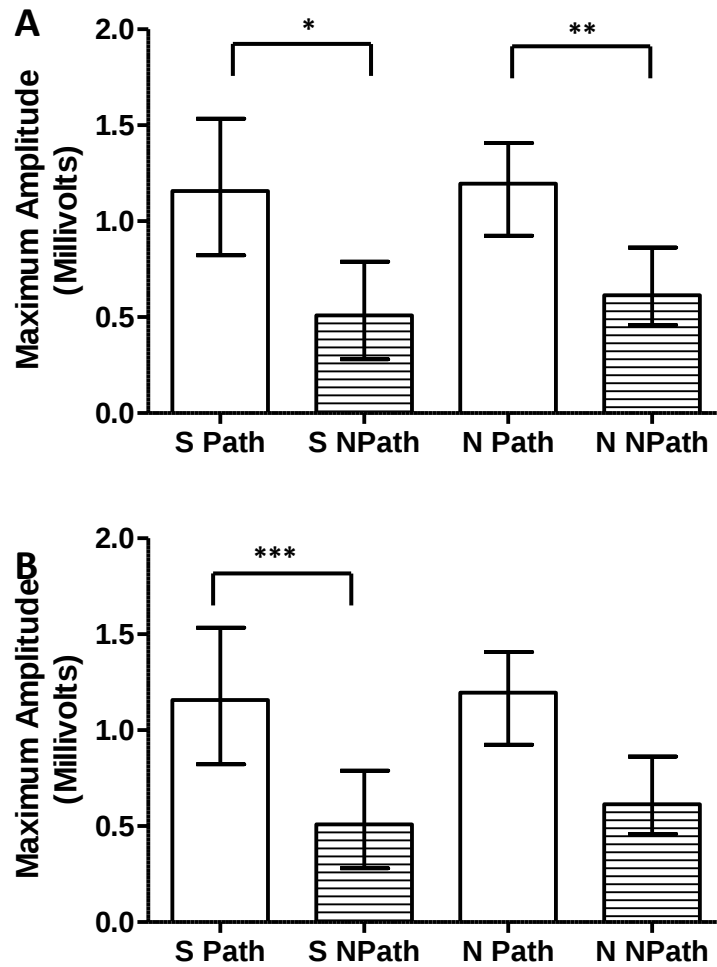


Figure 3.9: One-way ANOVAs run on maximum amplitude of gastrocnemius(A) and biceps femoris (B). S Path= students pathological, S NPath= students non-pathological, N Path= neurologists pathological, N NPath= neurologists non-pathological. U=25, $p<0.0001$; ** U=20, $p<0.001$; *** $t_{22}=3.77$, $p<0.001$.*

Discussion

This dissertation deals with numerous aspects of the Babinski reflex. These are: the technique used to elicit the reflex, the difference between a positive Babinski sign and a normal plantar flexion reflex, the inter-rater reliability of the reflex and the aspects of the reflex used for classification of a pathological or non-pathological response. In the discussion that follows I examine these aspects of the Babinski reflex by first considering the variability in techniques used to elicit the Babinski reflex, followed by how the variations in a stimulus affect the resultant reflex response. I then consider the differences, kinematically and electromyographically, between a positive Babinski sign and the normal plantar flexor response. Next I discuss the inter-rater reliability of the reflex, found in phase 3, compared with the data relating to inter-rater reliability seen in previous studies. Lastly I discuss the aspects shown to be used by raters when classifying if a Babinski reflex is pathological or non-pathological.

4.1. Variability of the technique used by neurologists when eliciting the Babinski reflex

The specialized custom built Babinski hammer enabled the pressures exerted by the neurologists, as they were performing the reflex, to be determined. These pressures represent the intensity of the stimulus applied to the foot. It is likely that different pressures are needed to elicit the reflex on different people. Thus in the first phase of this dissertation one person's foot was used as a standardized model of a foot where the Babinski reflex could be assessed and the repeatability of five strokes performed by each neurologist, as well as differences in technique between neurologists, could be assessed.

Post hoc analysis of the data from phase 1 revealed that the neurologists in this study used one of two techniques to elicit the plantar reflex in the subject. One third (4/12) ran the hammer along the centre of the foot without curving in towards the hallux; while the rest (8/12) used the conventional method of running the hammer along the lateral plantar border

and curving in towards the hallux. Dohrmann and Nowack (1973) have shown that the optimum area for eliciting the reflex is along the lateral plantar border and across the medial arch of the foot. Therefore eight of the 12 neurologists made use of the optimum area. It was noted in this study that reflex activity appeared to usually occur when the stimulus reached the transverse arch which is part of the optimal area for eliciting the reflex. A possible explanation for the reflex apparently being activated at this point is likely due to the summation of action potentials in the muscles that take part in the reflex response. At this point therefore, a combination of the action potentials from all previous mechanical stimuli reaches the threshold needed for activation of the muscles responsible for movement of the foot and toes. This is important to note as the four neurologists that did not curve the hammer along the lateral plantar border

One area of focus when investigating the variation in technique of different neurologists was the intra-repeatability of the neurologists manoeuvre. The applied pressure for each stroke and time taken for each stroke, when performing five separate strokes was explored. There was a large amount of variation in both the maximum pressure and the average pressure a neurologist used for each stroke based on the coefficient of variance. Only two out of the twelve neurologists (16.66%) displayed a technique of consistent maximum pressure. When the variation in the average applied pressure was assessed only one out of twelve (8.33%) displayed low variation. In contrast, the time taken for each stroke had a higher repeatability with half of the neurologists (50%) obtaining low variation in the five strokes. It was also noted that the neurologists in general make use of a much quicker stroke time (median 2s; IQ ranges 1.53-3.86s) than advised (5-6s). Therefore it appears that the neurologists have difficulty repeating the same pressure on consecutive strokes. As only half of the neurologists obtained low variations for the duration of the stroke it is difficult to say from the data if neurologists do in fact use the same time for each stroke.

The inter-repeatability between the neurologists showed very high coefficients of variance for all variables. The greatest variation was seen for duration of hammer stroke followed by maximum hammer pressure and lastly average hammer pressure. This demonstrates that in a group of neurologists there is a wide variety of pressures and durations used to elicit the reflex.

There are implications for the lack of precision of technique (low variation) within and between neurologists. In order to interpret the Babinski reflex three rules are generally considered to be clinically important (see section 1.3.2.). One of these rules is that the reflex should be reproducible (van Gijn and Bonke, 1977, van Gijn, 1995). However neurologists do not use the same pressures repeatedly. Also two neurologists assessing the same foot do not apply the same pressure. This could affect the reflex as making use of a higher pressure may lead to a voluntary withdrawal or a startle reaction (Kugelberget *al*, 1960) which could lead to hallux dorsiflexion in patients with completely functional UMN pathways and therefore confusion as to if the sign is positive or negative. As a result, this may lead to high inter-observer variation between neurologists when assessing a reflex. This will be discussed further in section 4.4 where the clinically important inter-rater reliability of the rating of the Babinski response, is a specific focus.

4.2. Relationship between input variables (application, pressures and duration) and objective output variables (reflex muscle activity, movement and perceived pain)

Certain aspects of the resultant reflex from the neurologists numerous strokes were shown to be correlated to the pressures and timing data. These aspects were the biomechanical change in hallux angle and the VAS pain scales the participant completed for every reflex.

For the first time an objective three dimensional measurement of the change in hallux angle assessed the degree of movement of the hallux during the Babinski reflex. It is known that the

hallux has the largest degree of movement of all the toes, which is attributable to the anatomical structure of the metatarso-phalangeal joints (van Gijn, 1995). The movement of the hallux is therefore most often used to assess the reflex. The participant who acted as a subject in this study was healthy and as was expected the hallux moved in a downward direction (plantarflexion). A notable feature of phase 1 from this dissertation was that the plantar flexion movement was often not visible to the naked eye but the kinematic assessment showed that the hallux was in fact moving. Positive relationships were found between the change in hallux angle and all of the input variables. Therefore the greater the amount of pressure applied to the foot the larger the degree of movement of the hallux. In addition the longer the duration of the stroke, the larger the degree of movement of the hallux. As the neurologists in this study had very quick stroke times this could account for the small amount of movement of the hallux recorded in the participant.

The scores from the VAS evaluated the pain felt by the participant induced by the 'scratching' of his foot for every stroke. Duration of the stroke and the VAS score were not significantly related. This shows that the subjective pain felt by the participant was not influenced by the length of time the stimulus was applied. However positive relationships were found between the VAS scores and the maximum and average pressures. Hence the greater the pressure applied the more pain the participant felt. It is worth noting that this finding suggests that even though an application pressure which is of great enough magnitude to be a noxious stimulus is not usually required to elicit the Babinski reflex in a patient with an UMN lesion, clinicians in this study, generally used such a pressure. The use of this high level of pressure could possibly be a learned practice of these clinicians which does not take into account the different sensitivities found in different people.

In relation to muscle contraction, which may have been correlated to the nature of how the stimulus for the Babinski sign is elicited, it is well documented that the *tibialis anterior* is the

prime muscle of dorsiflexion (Marieb and Hoehn, 2010). In a normal healthy response the *tibialis anterior* is active and causes the foot to flex upwards (dorsiflexion). There were no significant relationships found between the maximum amplitude of the *tibialis anterior* and any of the input variables. Thus it can be concluded (as would be expected) that the amount of pressure applied to the foot or the duration of the stimulus has no effect on the degree of muscle activity in the *tibialis anterior* in the resultant reflex in a normal healthy individual.

Studies have been done on the effects of electrical stimulus strength on the plantar reflex and Babinski reflex responses (Kugelberg *et al*, 1960, Grimby, 1963 and Nakanishi *et al*, 1974). Both Grimby (1963) and Kugelberg *et al* (1960) found that the stronger the electrical stimulus the stronger the corresponding activity of various muscles. The methodology is similar in both papers in that they used needle electrodes positioned at the sole of the foot to provide the stimulus. EMG was recorded in the *tibialis anterior* as well as other muscles involved in the flexion and extension of the foot and toes. Both studies used healthy individuals. These results differ from the results obtained in the study in this dissertation as here the intensity of the stimulus was not found to have any effect on the muscle activity. However these studies used electrical stimuli and the current study used mechanical stimuli. Studies investigating differences between electrical and mechanical stimuli have shown that the two methods cannot be compared (van Gijn, 1975 and Nakanishi *et al*, 1974). Electrical stimulation, not only fails to imitate the clinical method, it also produces different results to mechanical stimulation (Nakanishi *et al*, 1974). Moreover it is more likely to evoke muscle activity in the *extensor hallucis longus* in normal healthy participants (van Gijn, 1975). The *extensor hallucis longus* is the main muscle responsible for the up going movement of the hallux. Consequently an electrical stimulus can produce a false positive Babinski sign. The differences seen between the two methods are probably due to a lack of summation of action potentials with electrical stimulation.

To date only two studies have looked at the effects of the degree of mechanical stimuli on the plantar and Babinski reflexes (Roby-Bramiet *al*, 1989 and Lee *et al*, 2011). Roby-Bramiet *al* (1989) found no relationship between the stimulation force and the size of the response, gauged by EMG of the *extensor digitorum longus* and the *flexor hallucis brevis*. A blunt steel probe that was fixed to a force transducer was used to elicit the reflex and record the force used. All of the patients in the study had a clear Babinski sign and paraplegia. Due to the paraplegia the reflex was tested while they were seated in their wheelchairs and not the usual supine position. Lee *et al* (2011) conversely did not measure the exact stimulus magnitude but rather differentiated between a hard and light stroke based on where the examiner held the hammer. A hard stroke was elicited by holding the hammer near the tip that is positioned on the foot and a light stroke by holding the middle of the hammer while eliciting the reflex (Lee *et al*, 2011). The results showed that a hard stroke could elicit an up going hallux in healthy subjects (Lee *et al*, 2011). This could be misinterpreted as a positive Babinski reflex therefore pressure should be applied cautiously. Thus the stimulus does not need to be painful and just needs to be firm enough to elicit a repeatable response (Lee *et al*, 2011).

These studies (Roby-Bramiet *al*, 1989 and Lee *et al*, 2011) had different methodology and assessed the degree of stimulation differently. The output variables differ as one study used EMG activity (Roby-Bramiet *al*, 1989) to assess the reflex response and the other used a subjective rating of flexor or extensor by the examiner (Lee *et al*, 2011). The EMG results from the current study are in agreement with Roby-Bramiet *al* (1989) in that the strength of the stimulus had no effect on the size of the EMG response. However Roby-Bramiet *al* (1989) tested patients with a positive response and the current study looked at only one participant with a flexor plantar response. Also the muscles assessed were different between the current study and Roby-Bramiet *al* (1989). The results found by Lee *et al* (2011) cannot be compared with the results seen in the current study as the method of assessing the reflex

was not the same. Since no other studies have assessed the degree of movement of the hallux as measured accurately with the use of kinematics (or other exacting methods), it is unfortunate that to date no comparisons with comparable data can be made.

The limitations of the current study are that only one participant was used and therefore any results obtained might possibly be particular to the participant. A future study looking at the accurately measured pressures and the outputs of the reflex in a varied pool of subjects/patients is therefore advocated.

The data from the first study (phase 1) of this dissertation would suggest that a large variety of pressures and durations are conventionally used by clinicians when eliciting the Babinski reflex. The variation in pressures and durations can cause a variation in the degree of movement of the hallux. It is notable that this could potentially lead to an increase in inter-observer variation when rating a reflex as every neurologist applies a different pressure and therefore will observe a slightly different response. In my opinion (and in agreement with both my own findings and that of Lee *et al*, 2011), I would suggest that a lighter stimulus than is currently used clinically (as seen in the clinicians participating in this study), be used to test for the Babinski sign. Clinicians who generally apply a greater pressure than is necessary and which may induce unwanted dorsiflexion of the toes could be trained with a device similar to our own or that of Roby-Bramiet *al* (1989). It is my opinion that the lightest stimulus that can be used and still obtain a repeatable response is therefore the best because it may possibly lower the chance of obtaining a false positive Babinski sign in a healthy person. It has also been found (Dohrmann and Nowack, 1973, Walker *et al*, 1990) that the stroke should be slower than the stroke times currently used by the clinicians participating in this study. Making use of a set stroke time could also aid in decreasing variation between clinicians when eliciting the Babinski reflex.

4.3. Patients with a positive Babinski sign vs. control participants with a normal plantar flexor reflex response

Patients with positive Babinski signs were compared with healthy age matched controls with negative normal Babinski/plantar reflexes. The controls had downward flexor responses with a wide variation as to the degree of the response. A wide variety of reflex responses is common in healthy individuals (Lee *et al*, 2011). A wide variation was also seen in the pathological (patient) group. Since it was previously shown that the pressure applied to the foot can vary the resulting reflex response the pressures used in this study were compared to ensure that any variation between the patients and controls wasn't caused by a variation in the pressure applied. No significant difference was found between both the maximum and the average pressure for the pressures applied to patients and controls. However there was a significant difference found between the patients and the controls for the duration of stroke, showing that a longer stroke time was used on the controls. There was no significant difference in the size of the feet between the controls and the patients therefore a slower stroke must have been used for the controls. A possible reason for this may have been that the assessor completed the whole stimuli trajectory under the sole of the foot of the patients with a quicker stroke than used on the controls. Another possible reason could be the faster responses found in the patients which caused the applicator of the stimulus (the current author: CLD), to remove the hammer slightly sooner from the patients feet than from the controls feet. The small variation in the stimulus duration, however, is not a likely explanation for the other differences found between the patients and controls.

The kinematic variables: absolute change in hallux angle, time to maximum hallux angle, change in ankle angle and time to maximum ankle angle, were not found to be significantly different between the patients and controls. This suggests that there is no difference in the speed or degree of both foot and toe movements for patients and controls. A significant

difference was shown for change in hallux angle but this represents the direction that the toes moved, patients moving upwards and controls flexing downwards. This finding is completely consistent with the observations first described by Babinski (1896). In contrast to the diagnostic importance of the hallux angle itself, the absolute change in hallux angle did not show a significant difference therefore showing that the degree of movement was not different between the groups. The electromyographic variables were also not significantly different between the patients and controls except for the maximum amplitude of the *tibialis anterior* muscle which was lower in patients than in controls. Reflex activity was found in the *gastrocnemius* in both the patients and the controls. Even though, as mentioned previously, it can be used as a flexor of the knee under certain conditions *gastrocnemius* is known to be responsible for plantar flexion of the foot. For this reason the activity found in *gastrocnemius* in this study could be due to an antagonistic reflex response following the initial dorsiflexion of the foot. Movement latency was found to be significantly different between the two groups with patients exhibiting lower movement latencies. This shows that the reflex response in patients was more quickly activated than it was in the controls. However the shorter movement latencies found in the patients could also be due to the quicker strokes used to elicit these responses.

The normal plantar reflex and the pathological Babinski reflex are both part of flexion synergy (Sherrington, 1910) therefore both of the responses involve the dorsiflexion of the foot (Kugelberg *et al* 1960, Lee *et al*, 2011) and the shortening of the leg (van Gijn, 1995). Uysal *et al* (1999), for example, have shown that there is muscle activity in the *biceps femoris* upon plantar stimulation in both healthy people and people with pathological conditions. It is hence not surprising that there was no significant difference between the degree and speed of foot movement among the patients and controls. This could also account for the similarity in muscle activity of the muscles involved in flexing the leg. The major

electromyographic difference between the normal response and the pathological response is recruitment of the *extensor hallucislongus* into contraction with the *tibialis anterior* (Landau and Clare, 1959 and van Gijn, 1976). This could account for the decrease in muscle activity in the *tibialis anterior* in the patients compared with the controls. As the *extensor hallucislongus* is responsible not only for extending the hallux but also for dorsiflexion of the foot (Marieb and Hoehn, 2010) it most likely lightens the load of the *tibialis anterior* and as a result less muscle activity is recorded.

A common misconception of the Babinski reflex is that it has to be slow (van Gijn, 1996a). The decreased movement latency for the patients compared with the controls shows that the response can be brisk. This difference is not due to height as no significant difference was found between the heights of the two groups. Height is known to be correlated to axon length and hence the length of the reflex arc, which ultimately correlates to reflex duration (Frijnset al 1997, Péréonet al 2004).

To our surprise, no study after Babinski (1896), has objectively looked at a direct comparison between the normal response and the pathological response. For this reason the results from this study cannot be supported with past research. Due to the small sample sizes of patients and control subjects used in this study, conclusions that emanate from this study should be viewed as preliminary. A few of the variables that were compared were close to being significantly different for the patients and controls and therefore repeating the study with a larger sample size may yield different results.

4.4. Inter-rater reliability of the rating of the plantar response

The inter-rater reliability for the current study was assessed by means of a video recording of the Babinski or plantar reflex. The video recordings were necessary to standardize the reflex seen by the neurologists and students and eliminate possible variations in eliciting the reflex

(different pressures and timings as discussed in section 4.1). Therefore it is hypothesized that the inter-rater reliability of the recorded reflexes would be higher than that found when looking at the variation between both how the reflex is elicited and how it is rated. Furthermore the videos showed only the foot and toes of the subject from the plantar view. From this angle flexion synergy of the leg cannot be accounted for and therefore it is not possible to assess if this is an important part of what neurologists use to assess the reflex.

Neurologists had a kappa value of 0.72 showing substantial agreement between raters. The kappa value for medical students was slightly lower than that seen for neurologists although it is still classified as substantial agreement. Removing the variability from how the reflex is elicited likely lead to a considerable increase in the agreement between the raters. This was even seen amongst medical students who have much less experience with the reflex than do neurologists.

Previous studies have showed a wide variation in the agreement between raters of the Babinski sign. Van Gijn (1996b), in similar research to phase 3 of this dissertation also asked neurologists to rate recorded videos of the Babinski reflex showing only the foot. Van Gijn showed poor to fair agreement with kappa values ranging from 0.09 to 0.28 which generally showed lower values than those found in the present study (kappa values ranging from 0.67 to 0.72). The difference is possibly due to the advancements in video recording technology (higher resolution digital videography) and hence the improved quality of the videos used in the current study. Maher *et al* (1992) showed an inter-observer kappa of 0.17. Miller and Johnston (2005) found the rating of the Babinski reflex to have an inter-observer kappa of 0.30. The low reliability found in these latter studies is likely to be methodological in nature(differences are likely to have occurred due to non-uniform application of stimuli and differing techniques of the physicians involved).Lee *et al* (2011) looked at both inter-observer reliability and inter-rater reliability. The inter-observer reliability was assessed by

the agreement between two examiners testing the Babinski reflex of 32 participants. The inter-rater reliability, in turn, was assessed by the agreement of two raters looking at 68 recorded reflexes. The reliability for the observers was found to be lower than that for the raters (kappa of 0.43 vs. 0.62) (Lee *et al*, 2011). A study comparing the reliability of the Babinski sign to Gordon, Chaddock and Oppenheim signs found that the Babinski reflex was the most reliable with a kappa of 0.55 (Singerman and Lee, 2008). Cook *et al* (2009) tested the diagnostic accuracy of a number of tests when diagnosing myelopathy. One of these tests was the Babinski reflex and it was found to have an inter-observer kappa of 0.56 (Cook *et al*, 2009). Another study found the inter-observer agreement to be moderate (kappa=0.59) (McCanceet *al*, 1968).

The rating scales used to assess the reflex were different for each study. Three of the above studies, allowed their raters two options (Maher *et al*, 1992, Miller and Johnston, 2005 and Singerman and Lee, 2008), three options were used in two studies (McCanceet *al*, 1968, Cook *et al*, 2009) and four options were used in one of the above mentioned studies (Lee *et al*, 2011). The current study used a rating scale of only two options, pathological and non-pathological. The other studies that used rating scales with two options showed much lower inter-observer variation than that found in the present study. Making use of a two point (flexor or extensor) scale however has been shown to lead to higher agreement than with a three point (flexor, extensor and equivocal) scale (kappa of 0.75 vs. 0.39) (Vogel, 1992). The equivocal (no discernable upward or downward movement) responses may appear that way to the naked eye although with kinematic measurements it was observed that the hallux still moved even if it could not be seen. This could explain the high percentage of equivocal responses seen in the normal population (Lee *et al*, 2011). A more accurate way to measure this slight movement (like kinematics) could eliminate variation found with subjective rater assessments.

The differences seen between the kappa values of the present study and those shown in past research could be for a variety of reasons. The different methods of eliciting the reflex could account for the variation in kappa values. The data reported by Lee and colleagues (2011) agrees with the hypothesis that removing the variation of the method of elicitation leads to higher inter-rater reliability. The differing methodology of the studies and different sample sizes could also lead to the observed variation in findings. The low agreement seen in most studies could be because of a lack of patient information. Vogel (1992) has shown that patient history as well as performing a full neurological examination increases the inter-observer agreement. This is supported by van Gijn and Bonke (1977) who highlighted the biasing effects of patient history on the rating of the Babinski reflex. The diverse rating scales used could also explain the wide variety of results in these studies.

A limitation of the present study is that it does not emulate the clinical setting. This was however necessary to remove the variation caused by how the reflex was elicited and to allow an assessment of only how the response is rated to be standardized.

The results of the current study show that the agreement on how a Babinski reflex response is interpreted is substantial between neurologists and medical students. A possible reason for the substantial agreement found in this study could be due to the elimination of variation brought about by eliciting the reflex.

4.5. Aspects of the Babinski reflex that predict classification

The features of the Babinski reflex that are used by raters to inform their subjective assessment of the reflex have not been assessed. There are guidelines of what should be looked for when assessing the Babinski reflex, namely looking for contraction of the *extensor hallucis longus* and simultaneous contraction of other muscles in the leg (Raijmakers *et al*, 1991, van Gijn, 1995 and Kumar *et al*, 2000). Whether these features of the Babinski reflex

play a role in judging if a Babinski reflex is pathological or not, was previously tested by Raijmakers *et al.* (1991) and showed an increase in inter-rater reliability. The reason that palpitation of the muscle contractions was not done is because the goal of the study was to assess the Babinski reflex objectively and the palpitation of the muscles could only be recorded subjectively. For this reason electromyography was used to assess any electrical activity in the muscles of the leg that would result in tremors of the muscle but which could be recorded objectively. Another reason palpitation was not assessed is due to the design of the study in which raters all viewed the same recorded reflex and therefore could not palpitate the participants' muscles. Van Gijn and Bonke (1977) tested whether asking raters to specifically focus on these aspects improved the inter-rater reliability, however they could not definitely evaluate if these aspects were taken into account by raters. By objectively measuring key aspects of the reflex it was possible for us to assess the aspects of the reflex that predict classification. These aspects were the degree and speed of movement of the hallux and the foot, the swiftness of the reflex response and the muscle activity of the muscles used for dorsiflexion of the foot (*tibialis anterior*) and flexion of the knee (*gastrocnemius* and *biceps femoris*). As both neurologists and students rated the reflexes we were also able to compare the aspects looked at by both groups.

The only aspect not shown to be correlated to the ratings of neurologists or medical students when assessing the Babinski reflex was the maximum amplitude of the *tibialis anterior*. As it was impossible for the rater to see the muscle activation the maximum amplitude of the *tibialis anterior* muscle would simply represent the resultant movement. The *tibialis anterior* is responsible for dorsiflexion of the foot which occurs in both normal individuals and patients with positive Babinski responses therefore it is not surprising that this aspect does not indicate whether a reflex is pathological or non-pathological.

Four aspects appeared to be used by both medical students and neurologists to differentiate a pathological from a non-pathological response. The first, and most obvious, was the change in hallux angle. The non-pathological responses had downward or equivocal movement while the pathological responses had upward movement. The second is the time to maximum change in ankle angle. This measured the speed of foot movement and was lower in the pathological rated reflexes than in the non-pathological rated reflexes. Therefore the raters were likely to have associated faster dorsiflexion of the foot with pathological reflexes. Movement latency was the third feature of the reflex, shown to be related to the diagnoses offered by medical students and neurologists. The movement latency was reduced in the reflexes rated as pathological compared with those rated as non-pathological. Thus the faster reflex responses were rated as pathological. The last aspect was the maximum amplitude of the *gastrocnemius*. This was decreased in the reflexes rated non-pathological. The *gastrocnemius* (as stated previously) is responsible for flexion of the knee; therefore less muscle activity in this muscle is most probably related to a lesser degree of flexion of the knee.

The pathological reflex response is said to be a return to the plantar withdrawal response seen in infants (Zafeiriou, 2004). The plantar withdrawal response seen in infants is reported to be more brisk than the normal response and to encompass withdrawal of the entire leg (van Gijn, 2002). Hence the pathological response would include a more brisk response and withdrawal activity in the entire leg. This could therefore be what the raters are looking for when assessing a pathological response which would explain why change in maximum ankle angle, movement latency and maximum amplitude of *gastrocnemius* are key aspects used to classify the reflex.

The maximum amplitude of the *biceps femoris* was significantly different between reflexes rated as pathological and non-pathological by students only. This muscle, like the

gastrocnemius, plays a role in knee flexion. The maximum amplitude was lower in the reflexes rated as non-pathological by the students possibly due to the students associating flexion synergy with a pathological response.

In addition to the aspects mentioned above significant differences between the pathological and non-pathological neurologist rated reflexes were found for time to maximum hallux angle as well as change in ankle angle. The time taken to reach maximum hallux angle was less for the pathological rated reflexes than the non-pathological rated reflexes. Thus pathological reflexes were associated with a quicker moving hallux. The change in ankle angle was also lower in pathological rated reflexes. Therefore a greater degree of movement of the foot was rated as non-pathological by neurologists. Neurologists looking at the faster moving hallux can again be explained by the pathological reflex being described as brisk and thus neurologists relate briskness with a positive Babinski sign. A lesser degree of movement of the foot in the pathological rated reflexes might be linked to the experience of neurologists, who have more experience in assessing reflexes and may be able to subconsciously pick up on slight differences that the students cannot yet detect.

The results therefore show that it is likely that both students and neurologists do not look at the direction of the movement of the hallux alone. The speed of the reflex, as well as movement of the foot and knee could play a role in the classification of a pathological versus a non-pathological plantar reflex.

4.6. Conclusions

In summary, the studies making up the present dissertation, have firstly found that a wide variation in the technique used to elicit the Babinski reflex within and between neurologists exists. The variation in these techniques used to elicit the Babinski reflex was also found to be related to variations in aspects of the resultant reflex. Differing techniques of eliciting the

Babinski sign, could however be related to the large inter-observer variation seen in previous studies of the rating of the Babinski reflex. It was also shown in a comparison between patients with a positive Babinski sign and matched controls that the pathological response has less activity in the *tibialis anterior* muscle. Ratings of pre-recorded Babinski responses in this study were shown to have substantial agreement when both neurologists and medical students assessed them. The specific aspects of the reflex that both groups appeared to use to assess and differentiate between a pathological and a healthy response were: the speed of the reflex, the direction the hallux moved and concurrent withdrawal activity in the leg. Finally the research in this dissertation hopefully adds to the literature on the aspects involved in eliciting, interpreting and rating the Babinski reflex and thus allowing its use in clinical neurology to be optimized.

4.7. Future Studies

The results of the studies that make up the current dissertation have also lead to further questions regarding the Babinski reflex. The comparison between the Babinski reflexes of healthy individuals and individuals displaying a positive Babinski sign should be further explored with a larger sample size in order to see if the results found in this study are representative of a greater portion of the population. The ability to track the movement of the hallux in relation to muscle activity could also help with deciding if an up-going toe is representative of a positive Babinski sign. A study looking at participants with an equivocal plantar response and the synchronicity of movements of the hallux with muscle activity in the *tibialis anterior* and the *biceps femoris* could lead to a better understanding of what makes an equivocal response pathological or non-pathological. With the development of the specialized Babinski hammer the relationship between the pressures used and the features of the resultant reflex can now be further explored. It would be interesting to assess if there is a relationship between the pressures and the reflex response in a group containing both healthy participants

and patients with UMN damage. With the use of the specialized Babinski hammer it may be interesting to also assess the influence of stroke time on the resultant reflex and if a shorter or longer stroke elicits a better reflex. The development of a standardized subjective rating scale for the Babinski reflex may also contribute to improving the reflex's use in the clinical setting. This scale could potentially incorporate the three aspects of the Babinski reflex namely: Observation or palpitation of any contraction of the *extensor hallucis longus*; observation of contraction of other muscles in the leg; and that the response should be reproducible.

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Appendices

Appendix I: Informed consent sheet signed by the participants

**University of the Witwatersrand
School of Physiology**

Hello,

I, Chloe Dafkin, am a Masters student in the School of Physiology and I am running a project looking at two closely related spinal reflexes namely, the Babinski reflex and the flexor withdrawal reflex. The Babinski reflex is said to be one of the most important and clinically useful tools in the neurological examination. The flexor withdrawal reflex is also an established part of the clinical neurological exam and therefore it is important to be able to assess these reflexes accurately. The flexor withdrawal reflex is also often used in research studies as it is a non-invasive way to measure pain sensitivity.

It has been reported that many medical professionals find it difficult to differentiate the Babinski sign from movement of the toe that is connected to flexion synergy. The pyramidal tracts both decrease flexion synergy and inhibit toe extensors which is why when there is a lesion of the pyramidal tracts both flexion synergy and the Babinski sign present. Therefore the purpose of the current study is to examine both the Babinski and the flexor withdrawal reflexes together in the same participants in order to see if they do activate the same muscles and to quantify the similarities in movement patterns that may occur.

To help me discover this, I would like to invite you to volunteer for my project.



Figure 1

For accurate recordings to be taken I will put reflective markers and small recording devices (about the size of a R5 coin, see figure 2) on various parts of your legs and feet and use video cameras to capture your image and body movements into a computer model. The computer model will track and analysis the movement of your legs when we test your reflexes.

The reflexes involved are:

- **Babinski Reflex** – invoked by running a blunt object along the lateral plantar border of the foot, from the heel towards the great toe.
- **Flexor Withdrawal Reflex** – invoked by a noxious stimulus applied to the sole of the foot. Electrical shock stimulation will be used to elicit the reflex on the sole of the foot.

The reflex tests shouldn't take longer than an hour. The video cameras will only detect the white markers on your legs and not any features that could be used to identify you.

The results will be analyzed and published in a scientific paper and presented at a scientific conference, however your identity will remain anonymous. Your personal results will be made available to you if you wish.

My supervisors and I have obtained approval for this study from the Committee for Research on Human Subjects of the University of the Witwatersrand. Participation in this study is

voluntary and you are allowed to withdraw at any time. If after reading this information sheet you decide against participating in the study please be assured that this will not impact on you negatively in any way. If you have further questions please don't hesitate to ask.

We would like you to participate in the study and confirm your willingness to do so by signing the consent form overleaf.

Sincerely

Chloe Dafkin
082 540 2022
Chloe.Dafkin@gmail.com

UNIVERSITY OF THE WITWATERSRAND

Wits Biomechanics Laboratory, School of Physiology

CONSENT TO ACT AS A SUBJECT IN RESEARCH

1. I being 18 years or older , consent to participating in a research project entitled: 'The Relationship between Objective Kinematic and Electromyographical Measurements of the Babinski and Flexor Withdrawal Reflexes'.
2. The procedures have been explained to me and I understand and appreciate their purpose, any risks involved, and the extent of my involvement. I have read and understand the attached information leaflet.
3. I understand that the procedures form part of a research project, and may not provide any direct benefit to me.
4. I understand that all experimental procedures have been sanctioned by the Committee for Research on Human Subjects, University of the Witwatersrand, Johannesburg.
5. I understand that my participation is voluntary, and that I, as a participant, am free to withdraw from the project at any time without prejudice.

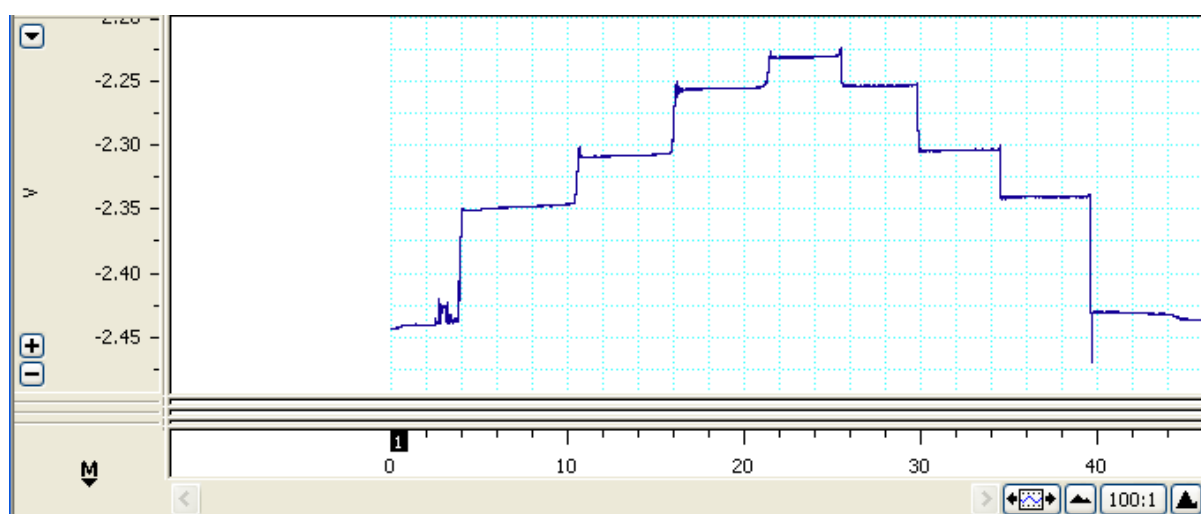
Subject name and signature

Date

Investigator name and signature

Date

Appendix II: Five point calibration curve for the Babinski hammer



Appendix III: VAS pain scale

Visual AnalogueScale (Pain) Test 1

On the line below mark a point that accurately reflects your current level of pain

No pain _____ Most severe pain

Visual AnalogueScale (Pain) Test 2

On the line below mark a point that accurately reflects your current level of pain

No pain _____ Most severe pain

Visual AnalogueScale (Pain) Test 3

On the line below mark a point that accurately reflects your current level of pain

No pain _____ Most severe pain

Visual AnalogueScale (Pain) Test 4

On the line below mark a point that accurately reflects your current level of pain

No pain _____ Most severe pain

Visual AnalogueScale (Pain) Test 5

On the line below mark a point that accurately reflects your current level of pain

No pain _____ Most severe pain

Appendix IV: The questionnaire giving to the neurologists and the medical students

Name: _____

Age: _____

Year of Study: _____

- | | | |
|-----|---------------------------------------|---|
| 1. | ☐ Pathological | ☐ Non-pathological |
| 2. | ☐ Pathological | ☐ Non-pathological |
| 3. | ☐ Pathological | ☐ Non-pathological |
| 4. | ☐ Pathological | ☐ Non-pathological |
| 5. | ☐ Pathological | ☐ Non-pathological |
| 6. | ☐ Pathological | ☐ Non-pathological |
| 7. | ☐ Pathological | ☐ Non-pathological |
| 8. | ☐ Pathological | ☐ Non-pathological |
| 9. | ☐ Pathological | ☐ Non-pathological |
| 10. | ☐ Pathological | ☐ Non-pathological |

11. ☐ Pathological

☐ Non-pathological

12. ☐ Pathological

☐ Non-pathological

13. ☐ Pathological

☐ Non-pathological

14. ☐ Pathological

☐ Non-pathological

15. ☐ Pathological

☐ Non-pathological

Appendix V.I: Foot plane

```
Foot_plane_pt1=Foot_Heel(count,:);
Foot_plane_pt2=Bottom_Big_Toe(count,:);
Foot_plane_pt3=Bottom_Little_Toe(count,:);
pt1=Foot_plane_pt1;
pt2=Foot_plane_pt2;
pt3=Foot_plane_pt3;

linept1to2i= (pt1(1,1) - pt2(1,1));
linept1to2j= (pt1(1,2) - pt2(1,2));
linept1to2k= (pt1(1,3) - pt2(1,3));
linept1to3i= (pt1(1,1) - pt3(1,1));
linept1to3j= (pt1(1,2) - pt3(1,2));
linept1to3k= (pt1(1,3) - pt3(1,3));

%doing the cross product to find the normal
A=[ linept1to2i linept1to2j linept1to2k ];
B=[ linept1to3i linept1to3j linept1to3k ];
normC = cross(A,B);
normCi=normC(1,1);
normCj=normC(1,2);
normCk=normC(1,3);
n=normC;
pt1xval=pt1(1,1);
pt1yval=pt1(1,2);
pt1zval=pt1(1,3);
Foot_plane_xvalconsta= normCi * pt1xval;
```

```

Foot_plane_yvalconsta= normCj * pt1yval;
Foot_plane_zvalconsta= normCk * pt1zval;
Foot_plane_const=
(Foot_plane_xvalconsta+Foot_plane_yvalconsta+Foot_plane_zvalconsta);
Foot_planeXval=normCi;
Foot_planeYval=normCj;
Foot_planeZval=normCk;
Foot_plane_Xconstant=Right_UpperLegplaneXval;
Foot_plane_Yconstant=Right_UpperLegplaneYval;
Foot_plane_Zconstant=Right_UpperLegplaneZval;
clear pt1
clear pt2
clear pt3
clear A
clear B
clear normC
clear linept1to2i;
clear linept1to2j;
clear linept1to2k;
clear linept1to3i;
clear linept1to3j;
clear linept1to3k;
Planeconst_Foot=[Foot_plane_XconstantFoot_plane_YconstantFoot_plane_Zconstant ];

```

Appendix V.II: Arch plane

```
Arch_plane_pt1=Bottom_Big_Toe(count,:);
Foot_plane_pt2=Bottom_Little_Toe(count,:);
Arch_plane_pt3=Foot_Arch(count,:);
pt1=Arch_plane_pt1;
pt2=Arch_plane_pt2;
pt3=Arch_plane_pt3;

linept1to2i= (pt1(1,1) - pt2(1,1));
linept1to2j= (pt1(1,2) - pt2(1,2));
linept1to2k= (pt1(1,3) - pt2(1,3));
linept1to3i= (pt1(1,1) - pt3(1,1));
linept1to3j= (pt1(1,2) - pt3(1,2));
linept1to3k= (pt1(1,3) - pt3(1,3));

%doing the cross product to find the normal
A=[ linept1to2i linept1to2j linept1to2k ];
B=[ linept1to3i linept1to3j linept1to3k ];
normC = cross(A,B);
normCi=normC(1,1);
normCj=normC(1,2);
normCk=normC(1,3);
n=normC;
pt1xval=pt1(1,1);
pt1yval=pt1(1,2);
pt1zval=pt1(1,3);
Arch_plane_xvalconsta= normCi * pt1xval;
Arch_plane_yvalconsta= normCj * pt1yval;
Arch_plane_zvalconsta= normCk * pt1zval;
```

```

Arch_plane_const=
(Arch_plane_xvalconsta+Arch_plane_yvalconsta+Arch_plane_zvalconsta);
Arch_planeXval=normCi;
Arch_planeYval=normCj;
Arch_planeZval=normCk;
Arch_plane_Xconstant=Arch_planeXval;
Arch_plane_Yconstant=Arch_planeYval;
Arch_plane_Zconstant=Arch_planeZval;
clear pt1
clear pt2
clear pt3
clear A
clear B
clearnormC
clear linept1to2i;
clear linept1to2j;
clear linept1to2k;
clear linept1to3i;
clear linept1to3j;
clear linept1to3k;
Planeconst_Arch=[Arch_plane_XconstantArch_plane_YconstantArch_plane_Zconstant ];

```

Appendix V.III: Hallux vector and hallux angle

```
Big_Toe_Vector=Bottom_Big_Toe(count,:)-Top_Big_Toe(count,:);
```

```
Planeconst_Arch=[Arch_plane_XconstantArch_plane_YconstantArch_plane_Zconstant];
```

```
norm1 = sqrt ( Planeconst_Arch(1,1) * Planeconst_Arch(1,1) + Planeconst_Arch(1,2) *  
Planeconst_Arch(1,2) + Planeconst_Arch(1,3) * Planeconst_Arch(1,3) );
```

```
% plane
```

```
norm2 = sqrt ( Big_Toe_Vector(1,1) * Big_Toe_Vector(1,1) + Big_Toe_Vector(1,2)  
*Big_Toe_Vector(1,2) + Big_Toe_Vector(1,3) * Big_Toe_Vector(1,3) );
```

```
% vector
```

```
Big_Toe_cosine = ( Planeconst_Arch(1,1) * Big_Toe_Vector(1,1) + Planeconst_Arch(1,2) *  
Big_Toe_Vector(1,2) + Planeconst_Arch(1,3) * Big_Toe_Vector(1,3)) / ( norm1 * norm2 );
```

```
Big_Toe_angle = 90+acosd( Big_Toe_cosine );
```

```
Chloe_Data(2,count)=Big_Toe_angle;
```

Appendix V.IV: Ankle angle

```
ifSelectLeg == 'l'
```

```
LKnJC = (Left_Lateral_Knee(count,:) + Left_Medial_Knee(count,:))/2;
```

```
LANKJC = (Left_Lateral_Ankle(count,:) + Left_Medial_Ankle(count,:))/2;
```

```
LeftFootVector=(Top_Big_Toe(count,:) -LANKJC);
```

```
LeftCalfVector=(LANKJC -LKnJC);
```

```
Left_Ankle_angle=atan2(norm(cross(LeftFootVector,LeftCalfVector)),dot(LeftFootVector,LeftCalfVector));
```

```
Left_Ankle_angle = 180/pi*mod(Left_Ankle_angle,2*pi);
```

```
Chloe_Data(6,count)=Left_Ankle_angle;
```

```
elseifSelectLeg == 'r'
```

```
RKnJC = (Right_Lateral_Knee(count,:) + Right_Medial_Knee(count,:))/2;
```

```
RANKJC = (Right_Lateral_Ankle(count,:) + Right_Medial_Ankle(count,:))/2;
```

```
RightFootVector=(Top_Big_Toe(count,:) -RANKJC);
```

```
RightCalfVector=(RANKJC -RKnJC);
```

```
Right_Ankle_angle=atan2(norm(cross(RightFootVector,RightCalfVector)),dot(RightFootVector,RightCalfVector));
```

```
Right_Ankle_angle = 180/pi*mod(Right_Ankle_angle,2*pi);
```

```
Chloe_Data(6,count)=Right_Ankle_angle;
```

Appendix VI: Details of manuscripts which have been prepared for submission to peer reviewed journals as a result of the research contained within this dissertation

Paper “Variability of the technique used by neurologists when eliciting the Babinski reflex” intended for submission to “Journal of Neurology”.

Paper “Comparison of measured variables of positive Babinski reflexes to healthy plantar flexor responses” intended for submission to “Neurology India”.

Paper “Reliability of the Babinski reflex for Diagnosing Pathology: Medical students vs. Neurologists” intended for submission to “Muscle and Nerve”.

Appendix VII: Details of papers published by the author of the current dissertation while registered for the current degree

Title: The patellar reflex: does activity of quadriceps femoris muscles reflect leg movement?

Journal: Neurological Research 2012; **34**: 623-626

Authors: Chloe Dafkin, Andrew Green, Samantha Kerr, and Warrick McKinon

Title: The accuracy of subjective clinical assessments of the patellar reflex

Journal: Muscle and Nerve 2013; **47(1)**:81-88

Authors: Chloe Dafkin, Andrew Green, Samantha Kerr, and Warrick McKinon