

An Investigation into the Epidemiology and Aetiology of Morton's Neuroma

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Abstract

Morton's neuroma (MN) is a common disorder affecting the forefoot. There is dearth of epidemiological studies on MN and there is a debate over the aetiology of this condition. This thesis describes a series of four studies investigating the epidemiology and aetiology of MN. The epidemiology section involves the description of hospital admissions for MN in Australia. The clinical section describes an investigation of the effect of foot posture, body mass, ankle equinus, various radiographic parameters, plantar pressure measurements and geometrical analysis of patients with and without MN.

The epidemiology study investigated the rate of admissions for MN from 1998 to 2008 in both private and public Australian hospitals. Data regarding admissions with a diagnosis code of ICD-10 G57.6 were extracted from the Australian Institute of Health and Welfare databases of hospital morbidity. There were 13,579 hospital admissions in Australia with a diagnosis of MN from 1998 to 2008. Admissions for this condition were almost three-fold higher for women compared to men. Among women admitted for Morton's metatarsalgia, the highest rate was in the 50- to 54-year-old age group. For men, the highest rate was in the slightly older 55- to 59-year-old age category.

The first clinical study presented here investigated the aetiology of MN in terms of a possible association between MN and foot type, as measured by the Foot Posture Index. The study also examined whether there was a relationship between foot type and the interspace affected with MN, and whether ankle equinus or body mass index were implicated. One hundred participants were recruited from The University of Western Australia's Podiatry Clinic, 68 of whom were diagnosed with MN and 32 were control participants. No significant differences were found between the controls and MN group with respect to the mean foot posture index scores of the left and right foot. Additionally, no significant differences were detected between the affected MN interspace and foot posture index. There was no significant difference in mean body

mass index between the MN and control groups. There was, however, a significant difference in mean ankle dorsiflexion between the MN and control groups.

The second clinical study included weightbearing radiographs of 101 subjects, of whom 69 were diagnosed with MN and 32 were control subjects without MN. A single assessor measured the following angles: lateral intermetatarsal angle, intermetatarsal angle, hallux valgus angle, digital divergence between the second and third digits, digital divergence between the third and fourth digits, relative metatarsal lengths of the first to fifth metatarsals, and the effect of MN size as measured by ultrasonography on digital divergence. Intra-tester reliability was assessed for all radiographic measurements. No significant differences in radiographic measurements were observed between the MN and control groups. Based on these results and in the absence of an irregular, lesser metatarsal parabola, it is difficult to justify metatarsal shortening as a routine surgical treatment for MN. Furthermore, no correlation was found between the size of MN, estimated using ultrasound images, and radiographic evidence of digital divergence

Finally, the third clinical study investigated whether there were differences in peak pressures, contact times, and pressure-time integrals beneath 10 masked areas under the feet of 61 patients with MN and 31 control subjects. In the same series, geometrical analyses derived from plantar pressure measurements such as forefoot width, foot length, coefficient of spreading, and foot progression angles of patients diagnosed with MN were compared to control subjects. We also investigated for correlations between increased forefoot peak pressures and forefoot width in subjects diagnosed with MN. No significant differences were observed in all plantar pressure and geometrical data derived from the plantar pressure measurements. Finally, no increase in the coefficient of spreading or increase in plantar pressures under the metatarsal heads were found, thus questioning whether the forefoot transverse arch collapses during the propulsion phase of gait.

In conclusion, ankle equinus was found here to be a significant factor in the pathogenesis of MN. Future studies should investigate the effect of stretching on management of MN.

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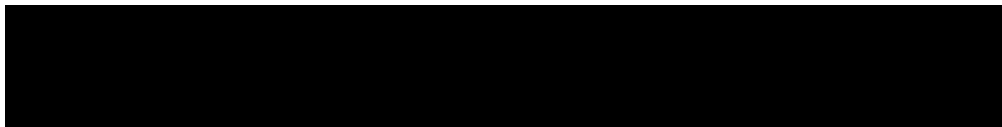
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Location in thesis: Chapter Three

Student contribution to work: The candidate performed data collection and interpretation of the results with help of Professor Linda Slack-Smith. The manuscript written by the candidate. The final manuscript was reviewed by both Professor Linda Slack-Smith and Professor Alan Bryant

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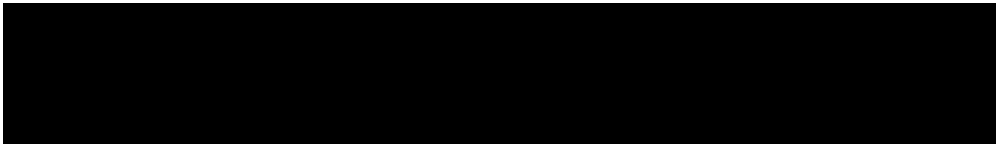
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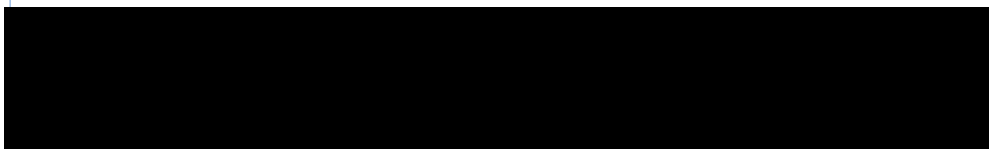
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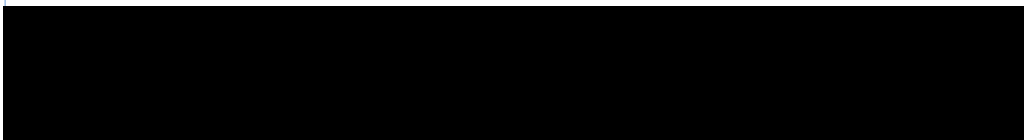
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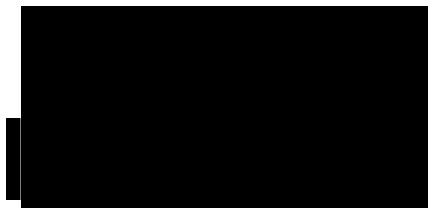
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Abbreviations

AIHW	Australian Institute of Health and Welfare
ADF	Ankle dorsiflexion
AI	Arch index
AOFAS	American Orthopedic Foot and Ankle Score
BMI	Body mass index
COS	Coefficient of spreading
DD	Digital divergance
DP	Dorso plantar
DTML	Deep transverse metatarsal ligament
FL	Foot length
FPA	Foot progression angle
FPI	Foot posture index
FW	Forefoot width
HAV	Hallux abducto valgus angle
ICD-10	International Classification of Diseases, 10th Revision
IM	inter-metatarsal angle
LIMA	Lateral intermetatarsal angle
MN	Morton's neuroma
UWA	The University of Western Australia

Chapter 1. Development of the Problem

1.0 Introduction

Morton's neuroma (MN) is one of the most common problems affecting the forefoot. The condition mostly affects women and it is more common in the second and third interspaces (1, 2). Most of the literature indicates that it more commonly occurs in middle-aged females, however, no evidence was found in the literature regarding the characteristics of the hospital admissions of this condition and its epidemiology (apart from work done through this thesis). Most research on the aetiology of Morton's neuroma has focused on case series investigation of diagnostic, conservative and surgical management of the condition. Despite being a relatively common condition, there is no consensus in the podiatric or medical literature as to the aetiology of MN (3). There are many proposed aetiologies of MN in the literature without adequate evidence such as case control studies. For instance, hyperpronation of the foot was mentioned by Morton (4) as the cause of MN without using a reliable method to measure foot posture of affected individuals compared to asymptomatic subjects. Furthermore, increase in pressure (5) and short first ray (6) have been implicated as the cause of MN but there are no studies in the literature measuring the metatarsal parabola in patients with and without MN. Accordingly, there is a need to investigate the possible aetiologies of MN, with case-control studies being a suitable approach.

Chapter One briefly describes the various problems and purposes of the individual studies contained within this body of research.

Chapter Two includes an overall review of the proposed aetiologies of MN, its diagnosis and management (both conservative and surgical). This is followed by a description of Foot Posture Index (FPI© Version 6), radiographic techniques to assess metatarsal parabola, and the EMED™(Novel.de) plantar pressure measurement system used to quantify pressure in the forefoot.

Chapter Three comprises a description of the epidemiology of hospital admissions for MN.

Chapter Four was an investigation of the relationship of foot type, body mass index (BMI), and ankle equinus with MN.

Chapter Five discusses radiographic analysis of MN and the effect of relative metatarsal lengths on MN formation.

Chapter Six is an investigation of plantar pressure and geometrical parameters of patients with and without MN.

Chapter Seven summarizes the pertinent findings of each preceding chapter, presenting conclusions and recommendations for future studies.

Note: Chapters Three to Six constitute research papers that have been published as a result of this research.

1.1 Statement of the Problem and Purpose of the Studies

1.1.1 Description of hospital admission for Morton's neuroma (Chapter Three)

Problem

Most of the literature suggests that MN occurs more commonly in middle-aged women (1, 7, 8). However there are no publications that report hospital admissions of MN in a large population prior to this work. Little is known regarding the age and sex of hospital admissions for MN in Australia.

Purpose

The purposes of this study were to:

- (i) describe MN admissions by patient sex and age group, using International Classification of Diseases, 10th Revision (ICD-10) diagnosis codes to

interpret total population data extracted from the Australian Institute of Health and Welfare (AIHW)

- (ii) measure the rate of admissions of MN in Australian hospitals
- (iii) observe the ratio of female to male admissions.

1.1.2 The relationship between foot posture index, ankle equinus, body mass index and inter-metatarsal neuroma (Chapter Four)

Problem

While a pronated foot has been proposed as the main foot type associated with MN (1, 7, 9), the relationship between foot type and MN has not been properly established. In addition, it is not known if the variability in the occurrence of MN in the second or third interspace has any relationship to foot type. Similarly, no previous case control studies have investigated the relationship between ankle equinus or body mass index (BMI) on MN formation.

Purpose

The purposes of this study were to:

- (i) investigate the association between foot type as measured by the Foot posture index (FPI), ankle equinus and BMI and the presence of MN
- (ii) observe if pronated and/or supinated foot predisposes to MN formation in the affected inter-metatarsal space.

1.1.3 Radiographic analysis of feet with and without Morton's Neuroma (Chapter Five)

Problem

There are no radiographic studies comparing the relative length of metatarsals in patients with and without MN. The increase in length of metatarsals is thought to cause irritation of the affected nerve (10). Elevation of the first metatarsal can increase pressure in the forefoot (6, 11), however its effect on MN formation is unknown.

Increase in the size of a MN is thought to increase deviation of the affected toes, a phenomenon called digital divergence. No study in the literature has investigated the effect of MN size, as measured by ultrasound, on the divergence of the involved digits.

Purpose

The purposes of this study were to:

- (i) assess the relative metatarsal length in patients with and without MN to observe if relative increases in length of the lesser metatarsals, or shortness of the first metatarsal, can cause MN
- (ii) investigate whether patients with MN have elevated first metatarsal compared to patients with no forefoot pain
- (iii) investigate if increases in intermetatarsal angle and hallux abductus angle have an effect on MN formation
- (iv) correlate the increase in size of MN, as measured by ultrasound, to the digital divergence angle.

1.1.4 Plantar pressure measurements and geometrical analysis of patients with Morton's neuroma and controls

Problem

It has been proposed that increased pressure in the forefoot over a prolonged period of time can damage the digital nerve leading to pain and discomfort. This has been implicated as an aetiology of MN (12-14). However, there are no reports in the literature of quantitative measurement of forefoot pressure to assess its possible effect on MN formation. Geometrical data, such as forefoot width and length, has not been studied in subjects with MN. It is assumed that the wider the foot the more prone it is to compressive forces leading to nerve irritation. Splay-foot has been implicated to predispose to metatarsalgia (15, 16). The relationship between peak pressure in the forefoot and forefoot width is unknown.

Purpose

The purposes of this study were to:

- (i) investigate the peak pressure, pressure time integrals and contact time of patients with and without MN
- (ii) investigate geometrical factors such as forefoot width, foot length, coefficient of spreading, and angle of gait with and without neuroma
- (iii) investigate whether there is any correlation between increased peak pressure in the forefoot and an increase in coefficient of spreading

1.2 Significance of the Study

MN is one of the most common clinical presentations in podiatric practice. Despite this, prior to this work there were no epidemiological data on the characteristics of hospital admissions for MN in the literature. Knowing the most common age category for hospital admissions will help the practitioner to identify the most likely age category that is at risk of hospitalisation for MN and will assist in planning services.

There is also no agreement in the literature regarding the aetiology of MN. A better understanding of its aetiology should help the foot and ankle specialist develop more appropriate treatments for MN. Currently, the management of MN focuses on the symptoms rather than the cause of the problem. For instance, one of the first lines of therapy for the management of MN is the use of corticosteroid injections that aim to alleviate the symptoms rather than treating the aetiology. In addition, understanding the aetiology can be very important in preventative care of a condition. For example, if a patient has ankle equinus and/or a pronated foot as diagnosed by careful physical examination, then it may be prudent to address these biomechanical faults if they are shown to be important factors in the development of MN.

The traditional standard of care in surgical management of MN is either to perform decompression neurolysis and/or excision of the nerve trunk. Again, these are aimed at alleviating the symptoms rather than the cause of the problem. More recently,

metatarsal osteotomy has been advocated as a surgical treatment to correct an ‘abnormal’ metatarsal parabola (10). The relationship between the metatarsal parabola and the formation of MN needs to be examined to justify such a surgical approach.

1.3 Hypotheses to be tested

- (i) MN admission in Australian hospitals is more common in middle aged women
- (ii) MN can occur in any foot type
- (iii) The location of MN is related to foot type
- (iv) The formation of MN is related to metatarsal length
- (v) MN is related to limited ankle dorsiflexion
- (vi) MN is related to geometric parameters of the forefoot
- (vii) Digital divergence is related to neuroma size
- (viii) Increased BMI is related to the formation of MN
- (ix) Increased forefoot plantar pressure is related to the formation of MN

Chapter 2. Literature Review

2.0 Introduction

MN is a painful condition in the forefoot . The incidence of MN in the general population has not previously been determined . The condition affects mostly women and is more common in the second and third interspaces (5, 17, 18). Despite being a relatively common condition, there is no consensus in the podiatric or medical literature as to its aetiology. Accordingly, there is a need to further investigate the proposed aetiologies of MN. A comprehensive literature review will be presented which includes the history surrounding the description of MN and why the term itself, which has been commonly used in the past, is a misnomer. The literature review will survey the proposed aetiologies, diagnostic testing and surgical procedures for MN. A review of the conservative and surgical management of MN will also be presented. Finally, a review of the literature relating to the equipment used to conduct the experimental studies will be presented.

2.1 Morton's Neuroma

Civinini, a professor of anatomy in Italy, first described a painful condition in the forefoot which later became known as "Morton's neuroma" . He described the lesion as a fusiform swelling in the common plantar nerve in the affected interspaces . He did not, however, recommend any treatment. In 1845, Durlacher, the Queen's surgeon-chiropodist, described a nerve impingement syndrome in the third web space of the foot (19). He treated the condition with shoe modifications. In 1876 an orthopedic surgeon from Philadelphia, T.G. Morton, described a painful condition in the forefoot which he treated by resecting the head of the fourth metatarsal in order to alleviate the pain (20). The condition was named after Morton and somewhat inappropriately termed Morton's 'Neuroma' .

Hoadley in 1893 was the first to describe a surgical procedure for MN which is still used today and involves surgical exploration and resection of the enlarged nerve (21).

Hoadley believed the metatarsal heads were impinging the nerve and hence causing pain and discomfort. The term “Neuroma” in Latin means a benign tumor of the nerve. The histological studies, however, demonstrated fibrosis of the epineurium and perineurium that occasionally invades the endoneural space. This was not representative of true neuroma, but indicated that entrapment and/or compression was the likely cause of this disease process (22-24). Hence the term “Neuroma”, which refers to a benign tumor of a nerve, is a misnomer. Other names such as Morton’s metatarsalgia (5, 25, 26), intermetatarsal neuroma (27-30), interdigital neuralgia (24, 31), and intermetatarsal neuritis have been used commonly in the literature to refer to this pathological condition.

2.2 Anatomy

The intermetatarsal nerves that pass in the affected interspaces are branches of the medial and lateral plantar nerves (Figure 2.1) (32, 33). The tibial nerve bifurcates at the level of the tarsal tunnel into medial and lateral plantar nerves which enter the foot through an opening over the abductor hallucis muscle belly called the porta pedis .



Figure 2.1 The anatomy of Morton’s neuroma (20)

The medial plantar nerve, the larger branch, continues distally between the flexor digitorum brevis and abductor hallucis muscles . At the level of the base of the first metatarsal it gives off its terminal branches to the big toe and the first common digital plantar nerves which travel into the first interspace .

The lateral plantar nerve also passes over the abductor hallucis muscle to enter the foot . The lateral plantar nerve crosses the foot laterally and lies between the flexor digitorum brevis and quadratus plantae muscle bellies. The nerve then pierces the lateral intermuscular septum and travels anteriorly to the level of the base of the fifth metatarsal where it divides into the superficial and deep branches. The deep branch travels medially between the adductor hallucis and the plantar interossei, giving branches to the fourth and third interspaces. The third interspace common plantar nerve may be a combination of the medial and lateral plantar nerve and some authors have proposed that it is this increase in size that predisposes it to develop a MN in the 3rd interspace (33).

The common digital nerves in the inter-metatarsal spaces lie deep to the deep transverse metatarsal ligament (DTML) along with the arteries, veins and the tendons of the lumbricalis muscles . As the common digital nerves pass underneath the DTML, they divide into the proper digital nerves that supply the opposing medial and lateral aspects of the corresponding toes. On the superior aspect of the DTML lie the interossei muscles, inter-metatarsal bursa, and branches of the superficial peroneal nerve. The bursa sometimes extends distally over the digital nerve distal to the DTML (34),

As the common plantar nerve in each interspace courses distally in the intermetatarsal space, there are numerous plantar directed branches . These plantar directed branches “are not present more than 4 cm proximal to the most proximal edge” of the DTML . Plantar directed branches are potentially a cause of recurrence of neuroma following surgical excision of the nerve .

Fibres of the DTML are connected on either side the metatarsals to the thickened part of the plantar capsule called the plantar plates. The plantar fascia is a broad band of the

ligament originating from the medial tubercle of the calcaneus and dividing into the superficial and deep slips at the level of the neck of the metatarsals. The deep slips attach to the medial and lateral aspect of the plantar plates and the DTML of the metatarsal phalangeal joints forming the longitudinal tie bar of the foot (35). This becomes important when the author discusses the digital stretch test during which the plantar fascia tightens as the toes dorsiflex. As the toes dorsiflex, the plantar fascia pulls the DTML and plantar plate proximally. This may explain increased compression of the nerves by the DTML.

2.3 Incidence and Epidemiology

MN is common in the female, middle-age population who wear high-heeled shoes, although it may also occur in the male population (2, 36-42). There is a dearth of epidemiological data on MN and the only population-based study was by Latinovic *et al.* (43). They analyzed data from 253 practices across UK from 1992 to 2000. The rate per 100,000 population for new presentations of MN diagnosis was 86 for women and 46 for men. For both sexes the highest rate of presentation was in the 55-64 year age category. The rate of hospital admissions for MN was 30 for females and 11 for males per 100,000.

It is generally agreed in the literature that the third interspace is the most common site for occurrence of MN, followed by the second inter-metatarsal space. Dockery found 80% of MN cases originated in the 3rd interspace. However, another study conducted by Keh *et al.* found the 2nd interspace to be more common in 70 patients treated for MN. It is generally agreed that the incidence of MN in the fourth and first interspaces is very rare (20, 44).

2.4 Aetiology

There are numerous aetiologies that have been suggested for MN, including trauma, ankle equinus, foot type, entrapment theory, bursa theory, anatomical theory, and metatarsus proximus theory.

2.4.1 Trauma theory

Although acute trauma such as crush injury, lesser metatarsal fractures, falling and stepping on an object have been reported as causes of MN (31, 45), repeated trauma to the forefoot can cause fibrosis around the common plantar nerves . Women wearing high-heeled shoes are potentially more prone to experience trauma throughout the stance phase of a gait cycle, which is possibly why MN is more common among women (5, 46).

Electron microscopic evaluation of MN shows oedema of the endoneurium, fibrosis of perineurium, axonal degeneration and necrosis, all of which suggest the nerve is traumatised by the adjacent structures (7). While some authors have stated that traumatisation occurs as a result of entrapment of the nerve against the DTML (47, 48), others have advocated involvement of the metatarsal heads (49, 50). This theory has not been tested in the literature. Betts *et al.* (51) investigated the relationship between plantar pressure and the development of MN in 270 feet diagnosed with MN. Plantar pressure was measured using pedobarography and 78.8% of subjects were found to have normal plantar pressure. These results indicated that excessive foot loading was not a factor in the development of MN. However, the Betts *et al.* study only assessed plantar pressures of the foot as a whole rather than assessing forefoot pressure, which is the anatomical site of nerve entrapment.

2.4.2 Ankle equinus

Equinus has been suggested by many researchers to be an important risk factor for the development of neuroma (13, 52, 53). Equinus is defined as “ankle dorsiflexion less than 10 degrees with the knee in extended position” (11). It is associated with prolonged wearing of high heel shoes and has been associated with many foot pathologies . With lack of motion at the ankle joint, the pathological forces of equinus are transmitted through the foot (52). The effect of equinus in diabetics has been studied by a number of researchers, all of whom showed increased plantar pressure in the foot (54-56). There have been many studies showing an increased incidence of forefoot ulceration in diabetic patients with ankle equinus deformity as a result of

increased forefoot pressure (55, 57, 58). Armstrong showed that by performing percutaneous Achilles tendon lengthening, the forefoot pressure could be decreased leading to healing of ulcerations in the forefoot (55). However, in a study published by Orendurff *et al.* in 2006, it was shown that equinus deformity accounted for only a small portion of the increased pressure in the forefoot (59). They used an Emed platform to measure the pressure in the forefoot of patients with equinus deformity and found that only 15% of the increase in forefoot pressure was due to ankle equinus deformity.

Barrett and Jarvis reported the treatment of a patient who had neuroma and equinus deformity with a gastrosolus recession. They believed that because of the increased forefoot pressure resulting from ankle equinus, the nerve becomes more entrapped between the DTML and the ground. Hence they believed there was a strong correlation between ankle equinus and neuroma, reasoning that if the abnormal equinus force is treated, the symptoms in the forefoot will be relieved. To the author's knowledge, there are no other studies in the literature that relate the treatment of ankle equinus to MN. Barrett and Jarvis reportedly tried gastrosolus recession on only one patient with MN. The relationship between equinus and MN will be examined in Chapter Four.

Common modes of compensation for ankle equinus are rear foot pronation, hypermobile flat foot, early heel-off, an abductory twist during propulsion, genu recurvatum, lumbar lordosis, and excessive hip flexion (60). Equinus causes hypermobility of the 1st ray when the Achilles tendon overpowers the stabilising force of the peroneus longus on the medial column. This may lead to a more pronated or pronating foot, which has been suggested as an aetiological factor in MN formation (61).

2.4.3 Foot type

Although most of the literature states that MN is associated with a pronated foot type (5, 11, 20, 28, 62-66), a supinated foot type has also been cited (8, 28, 30, 67). Another cause of trauma in the forefoot is abnormal shearing forces of the metatarsals in the forefoot area which may impinge the interdigital nerve. Root *et al.* believed that

shearing produced by abnormal pronation of the foot caused the painful condition of MN during the propulsive phase of gait . He proposed that trauma to the subcutaneous tissue increased the fibrosis around the nerve and speculated that because all metatarsals are unstable and hypermobile in pronation, this increased the chance of the nerve becoming impinged. In a pronated foot all the metatarsals evert and move in an anterolateral direction. This abnormal motion of the metatarsals may produce a crushing effect on the soft tissue beneath during the propulsive phase of gait (63). Hoadley also believed that 4th and 5th metatarsals had more motion than other metatarsals . This caused laxity in the transverse metatarsal ligament which allowed the common digital nerve to be impinged between the 3rd and 4th metatarsal heads. However, this mechanism does not explain the occurrence of MN in the 2nd interspace, which is also another common site for this pathology. In a study published by Kilmartin in 1994 in which the effectiveness of orthosis was studied in patients diagnosed with MN, no symptom relief was achieved following control of pronation, thus questioning the validity of pronation as a cause of neuroma (68).

Nilson *et al.* reported that MN occurred more in a cavus foot type (30). He argued that because of increased vertical forces on the metatarsal head in a cavus foot, the common plantar nerve was more susceptible to trauma. In his study he measured the calcaneal inclination angles and found that the incidence of neuroma decreased in the presence of a calcaneal inclination angle of less than 10 degrees. He also contended that because of an increase in the windlass mechanism in a cavus foot, the nerve is under greater stretching forces. However, because the study measured only one radiographic angle, it lacked sufficient scientific data to establish a relationship between the foot type and MN. Pazzaglia *et al.* reported in a histological study of 12 patients diagnosed with neuroma that two-third had cavus foot type and also proposed this condition was caused by a “mechanical pathogenic mechanism” .

2.4.4 Entrapment theory

Gauthier in 1979 was the first to treat MN as a nerve compression entity . He believed that during the last stage of the stance phase the anterior edge of the DTML entraps the

nerve and traumatises it. As a result, Gauthier proposed the DTML should be released in preference to resection of the nerve. In 206 patients he treated this way, 83% showed rapid and stable improvement in symptoms. However, Gauthier did not use a standardised scale to measure the subjective outcome of the surgical procedure, nor did he compare the outcome with that of nerve excision.

In 1984, a microscopic evaluation of MN was performed by Graham *et al.* . They found the nerve at the level of the distal edge of the deep transverse inter-metatarsal ligament showed an increase in diameter, increased blood vessels within the fascicles and increased fibrosis . Because of this finding they suggested the cause of pain was entrapment of the nerve against the DTML. However these authors did not examine the most swollen segment of the nerve relative to the DTML. In a cadaver study performed recently by Kim *et al.*, the entrapment theory was refuted because the enlarged nerve was located more distally relative to the DTML during simulated mid-stance and heel off stages of gait .

2.4.5 Bursitis theory

There is often a bursa present over the superior aspect of the DTML (69). Mulder was the first to mention that MN was connected to the inter-metatarsal bursa (49). A study by Bossley *et al.* found the bursa communicates with neurovascular structures distal to the deep transverse metatarsal ligament in all interspaces except the first and fourth (69). Inflammation around the bursa is thought to cause fibrosis of the nerve distal to the DTML (34, 70) and this may explain why MN is more common in the 2nd and 3rd interspaces.

2.4.6 Anatomical theory

Betts, Gauthier and Graham all believe that because the third common plantar nerve has branches from both the medial and lateral plantar nerves, it is larger and hence more prone to become entrapped and traumatised by the DTML (42). However, in a study on 50 human cadavers Frank *et al.* found that presence or absence of the communicating branch of the lateral plantar nerve made no difference to the size of the

common plantar nerve (32). In addition, this theory does not explain the occurrence of MN in the second interspace.

2.4.7 Digital stretch theory

As previously discussed, the plantar fascia inserts on the DTML in the longitudinal tie bar system (35). When the toes are dorsiflexed the plantar fascia tightens, pulling the deep transverse metatarsal ligament proximally. Cloke *et al.* suggested that by dorsiflexing the toes the nerve is also stretched and proposed a new method to clinically assess patients with MN. They performed the “digital stretch test” by dorsiflexing the ankle and dorsiflexing the adjacent toes in the affected interspaces. They found this test to be 100% sensitive in eliciting pain in 16 patients who were diagnosed with MN. Cloke *et al.* suggested this occurred because the nerve is stretched as a result of the toes being dorsiflexed.

In another study, Alshami *et al.* studied the effect of stretching the plantar nerves. He found there was an increase in strain on the medial and lateral plantar nerves when the ankle was dorsiflexed, foot everted and the toes dorsiflexed. They investigated this test using patients with plantar fasciitis and tarsal tunnel syndrome, but not patients with MN.

2.4.8 Metatarsus proximus theory

The term metatarsus proximus implies the heads of the metatarsals are so close to each other they allow little space between them. Metatarsus proximus can be identified on a standard weight-bearing dorso-plantar radiograph when two adjacent metatarsal heads are touching or seem to overlap one another (29). Anatomically, plantar to the deep transverse metatarsal ligament lie the lumbrical tendons and neurovascular structures. In its normal physiological state, the lumbrical tendon lies lateral to the common digital plantar nerves and courses dorsally along the proximal phalanx of the digit to insert medially on the base of the proximal phalanx. Guerin theorised that in metatarsus proximus the lumbricalis tendon is shifted more medially and positioned closer to the nerve. The constant brushing and irritation of the tendon on the nerve

during midstance and propulsion phase of gait can cause inflammation around the nerve and may therefore be an aetiological factor in the formation of MN.

In 1993 Grace *et al.* studied the relationship between metatarsus proximus and digital divergence in patients diagnosed with MN (29). Digital divergence is another radiographic parameter that has been seen in patients diagnosed with neuroma . Digital divergence is measured as the angle formed by the bisection of adjacent proximal phalanges. It is believed the enlarged nerve applies pressure at the base of the proximal phalanges, thus diverting them from one another. Grace *et al.* found that metatarsus proximus was more common in control, asymptomatic subjects than in those with MN. They also found a slight increase in the digital divergence angle in their neuroma group, but this was not statistically significant. However, they also reported a significant increase in the inter-metatarsal angle (IM) in the neuroma group, which seems at odds with their findings on metatarsus proximus. They proposed the inter-metatarsal angle is increased because the enlarged nerve pushes on the deep transverse metatarsal ligament, which can lead to an increase in the inter-metatarsal (IM) angle. A further issue with the study by Grace *et al.* is that the interspaces in which patients had been diagnosed with MN are not described.

Betts *et al.* studied inter-metatarsal spacing using ultrasonography, but found no statistical difference between toes in relaxed or extended position . However, this result is questionable as their measurements were made on non-weightbearing feet and because the ultrasound images of bone are not as sharp as those obtained from plain radiographs.

2.4.9 Ischemic theory

Nissen proposed in 1948 that MN occurred as a result of micro trauma leading to ischemia of the digital arteries (71). He observed that the plantar digital artery traveled with the digital nerve to undergo disruption of “the arterial wall, thrombosis, and incomplete recanalization” (5). Hence he believed that endarteritis of the digital artery led to ischemic changes within the nerve. However, in 1950 Ringertz and

Unander-Scharin observed the same phenomena in patients diagnosed with MN as well as in healthy control subjects (72).

2.4.10 Metatarsal length and sagittal plane theory

2.4.10.1 Short first metatarsal

Morton was the first to state that first ray insufficiency (73), which he described as a short first metatarsal, results in increased dorsal extension of the first metatarsal which can lead to MN formation (4, 74). Morton believed that hypermobility of the 1st ray leads to increased stress on the lesser metatarsals (74), which may in turn initiate the pathogenesis of MN as predicted by the trauma theory and ultimately lead to changes in the nerve.

Morton introduced the condition of “metatarsus ataviscus” or congenital short first metatarsal as a separate clinical condition and he later coined the term “Morton’s foot” (75). This shortness of the first metatarsal segment can lead to an increase in pronation in order for the first ray to purchase the ground (73). Brett *et al.* examined the relative length of the first metatarsal in 49 patients diagnosed with MN and 46 controls using Morton’s (6) and Hardy and Clapham’s methods (76). Surprisingly, they found that a short first metatarsal was more common in the control group than the MN group. To further confuse the issue of the importance of 1st metatarsal length, there have been reports of development of MN following shortening osteotomies of the first metatarsal (77). The research presented in this thesis will examine the relative lengths of all metatarsals using Maestro’s technique, which is often used during pre-operative planning of the surgical management of metatarsalgia (78).

2.4.10.2 Longer lesser metatarsals

Increased length of lesser metatarsals can increase forefoot pressure and hence forefoot pain (10). Park *et al.* performed shortening osteotomies on longer lesser metatarsals in patients affected with MN and found better outcomes than performing DTML release. There are no case control studies in the literature that compare differences in the length of lesser metatarsals in patients with and without MN.

2.4.10.3 First ray elevatus

First ray elevatus/ hypermobile first ray/ first ray insufficiency can result in dynamic imbalance between the first and lesser metatarsal segments (73). The first ray is imperative to foot function as a provider of shock absorption during gait. Approximately 60% of normal weight-bearing forces pass through the first ray from contact phase through propulsion (79). If the first ray cannot support the load, the medial column fails as a rigid lever with consequent arch collapse and load shift laterally to the lesser metatarsals. Overload of the lesser metatarsals may ultimately contribute to the development of lesser metatarsophalangeal synovitis, MN and/or stress fractures. First ray elevatus as a possible cause of MN has not been extensively studied.

Horton *et al.* studied first ray elevatus radiographically in 146 patients with hallux rigidus, 50 asymptomatic volunteers and 64 patients diagnosed with MN (80). They measured elevation of the first metatarsal in relation to the second metatarsal by determining the vertical distance between the two. In addition, they assessed the declination angle of the first metatarsal relative to the second metatarsal. They found no statistical differences between the three groups, but no measurement reliability results were reported by Horton *et al.* The measurements were performed manually using a tactograph to the nearest decimal point.

Bryant *et al.* (81) found an intra-rater reliability of 0.97 using a manual goniographic measurement technique when assessing first ray elevation of a group of patients with hallux limitus versus controls. More recently, computer technology can be used to make radiographic measurements, such as the IntelViewer System¹ computer program that can measure relative distances to two decimal places (82).

¹ <http://www.intelerad.com/en/products/inteleviewer/>

2.5 Clinical Presentation and Diagnosis of MN

MN presents with pain in the forefoot area that is sometimes associated with numbness and a burning sensation in the toes (24). The symptoms are often aggravated by wearing high heel shoes (2, 63, 83), presumably because high heeled and narrow shoes increase the pressure under the metatarsal heads thereby causing trauma to the nerve.

2.5.1 Clinical exam/tests

Clinical examination reveals pain in the plantar aspect of the interspace between the heads of the metatarsals (24, 84). Sharp *et al.* found pain upon palpation of the interspace was present in 100% of their case series (n=25) (84). Although not always present, Mulder's click is often present in patients with MN (5, 42, 46, 85, 86). Mulder's sign is performed by lateral compression of the forefoot, which may produce a palpable click (87). Mulder's click has been found to have a sensitivity of 98% in a case series of 43 subjects diagnosed with MN (88). Gauthier' test can replicate MN symptoms by squeezing the forefoot when a medial to lateral pressure is applied (86). Digital stretch test by Cloke and Greiss (89) is performed by dorsiflexing the lesser toes on either side of the affected webspace and with the ankle held in dorsiflexion and both feet on the examiner's knees. Pain or discomfort in the webspace of the affected foot indicates a positive result. This test has been reported to have a sensitivity of 100% and predictive value of 95% for diagnosis of MN (n=22). Finally, the injection of a small volume of local anesthetic may be given to assist with the diagnosis of MN (90).

2.5.2 Diagnostic imaging

Radiographs may be ordered to rule out other differential diagnosis such as stress fracture, arthritis, Freiberg's infarction, and abnormal metatarsal parabola. The phenomena of digital divergence can be observed on dorsoplantar (DP) radiographs as a result of enlargement of the bursa/neuroma complex exerting pressure on the base of proximal phalanges. Ultrasounds are a non-invasive modality frequently used to diagnose MN (38, 51). The typical sonographic appearance is that of an ovoid shaped

hypoechoic mass at the level of the metatarsal heads in the inter-metatarsal space (91). The sensitivity of ultrasound for the diagnosis of neuroma has been reported to range from 94% to 100% (91). Magnetic resonance imaging (MRI) is also highly sensitive for the detection of neuroma, but is expensive and not routinely ordered for this purpose in Australia. In one study, ultrasound was superior for the detection of MN compared to MRI, specially if the neuroma was less than 5 mm in size (85). A recently published meta-analysis showed that the sensitivity of ultrasound is equal to that of MRI for the identification of MN (92). Sharp *et al.* (84) and Pastides *et al.* (88) recommend that the diagnosis of MN should be clinically-based and that ultrasound and MRI should only be used where necessary to rule out other causes of pain in the forefoot such as plantar plate pathology, tenosynovitis/capsulitis, space occupying lesions, and presence of MN in adjacent interspaces. Furthermore, because there is a possibility of asymptomatic MN being reported in an interspace, as detected by ultrasound and MRI (93, 94), this may result in a false-positive clinical diagnosis of MN. In the research for this thesis, clinical examination with confirmatory ultrasound was employed to make the diagnosis of MN.

2.6 Treatment

Once diagnosis of MN is made, it is recommended that non-operative treatment should be attempted in the first instance (3, 5, 46). After failure of that approach, surgery may be advised (20, 86).

2.6.1 Conservative therapy

The conservative treatment of MN is varied and includes shoe modifications or footwear advice, metatarsal pads, foot orthoses, cortisone injections, alcohol injections and radio frequency ablation (95, 96). Patients are initially advised to wear wider toe box shoes and to avoid high heel shoes. Pads applied proximal to metatarsal heads can help by spreading the metatarsal heads and decreasing pressure on the nerve (20, 46). Modifications to footwear have been shown to improve symptoms in up to 41% (20) of patients but give lower satisfaction rates when compared with steroid injections (97).

Mann and Reynolds reported that 70-80% of patients did not respond well to shoe modifications and opted for surgery (45). Kilmartin and Wallace found pronation and supination orthoses to be ineffective in relieving pain (68).

Corticosteroid injections have been used to treat MN by reducing local inflammation around the lesion (98). They can be performed with or without ultrasound guidance. The real-time capabilities of an ultrasound scan allow continuous observation of needle placement into the targeted area while avoiding other soft tissue structures.

Rasmussen *et al.* reported that only 11% of 51 patients experienced lasting pain relief from cortisone injections after 4 years of follow up (46). Makki *et al.* studied the effect of single, ultrasound-guided cortisone injection for the treatment of MN (n=43) and found better outcomes for MN of less than 5mm in size (98). In their systematic review, Morgan *et al.* recommended that all injections for MN be done using ultrasound guidance in order to increase the efficacy of a single injection and decrease the need for additional injections (99). Mahadevan *et al.* in a double-blinded randomized control trial compared cortisone injection of MN with and without ultrasound (100). They found no significant difference between the outcomes of both groups and recommended that a clinician with knowledge of anatomy of the forefoot can safely perform the injection with good results and without relying on ultrasound guidance.

Dockery *et al.* reported 89% success using 4% alcohol sclerosing agents (28). He performed the injections in a series of 3-7 injections during a 5 to 10 day interval. Fanucci *et al.* used 30% alcohol and at 10 months follow reported a 20-30% reduction in mass of the MN (101). Ultrasound-guided alcohol ablation for the treatment of MN has been reported by some investigators as a safe procedure that significantly reduces pain in the short term (101-103). However, long term this does not offer permanent resolution of symptoms for most patients and can be associated with considerable morbidity (104).

Radio frequency ablation has recently been recommended by some authors, however, the efficacy of this treatment needs to be researched further (105). This treatment

involves insertion of a needle probe into the neuroma and generation of a high frequency, alternating current that causes heat necrosis of the nerve tissue. Chuter *et al.* reported a success rate of 85% in 25 patients with MN treated with ultrasound-guided radio frequency ablation (106). Other treatments such as phenol (20), Botulinum toxin A (107) and capsaicin (108) have been researched but are not part of the standard of care for the management of MN.

2.6.2 Surgical treatment

The surgical treatment of Morton's neuroma involves excision of the nerve (neurectomy) (34, 41), nerve decompression (109) via open or endoscopic release of the deep transverse metatarsal ligament (2, 34, 109, 110), and more recently, metatarsal osteotomies (10, 18, 111, 112). According to Hassouna *et al.* in a survey of foot surgeons, 68% perform neurectomy and 32% perform neurolysis with decompression of the nerve, while 8% perform neurolysis with release of the deep transverse metatarsal ligament only (113).

2.6.2.1 Neurectomy

Neurectomy is the most commonly described surgical procedure for MN (18, 20, 44) and can be performed via dorsal or plantar incision.

The traditional surgical approach is to resect the nerve proximal to the metatarsal heads . The success rate for neurectomy after follow up periods from 24-67 months has been reported to range from 70-93% (40). The main complication reported following this procedure is post-operative numbness and the potential for a painful recurrence in the form of a stump-neuroma (5, 46, 114, 115). The dorsal approach is thought by some to be technically easier than the plantar approach, but the nerve must be adequately resected at least 3 cm proximal to the inter-metatarsal ligament (20). The main advantages of the dorsal approach are prevention of painful scar formation or keratosis on the plantar surface of the foot, and the ability to bear weight immediately after surgery (64, 116). The main problem with dorsal incision is inadequate proximal resection of the nerve since this is physically more difficult because the nerve is plantar

to the DTML (64). Coughlin and Pinsonneault performed dorsal longitudinal incisions on 71 feet and reported good to excellent results in 85% of patients after an average of 5.8 years of follow up (116). Nery *et al.* reported a good result in 89% of 180 MN patients who underwent plantar transverse incisions after an average follow up of seven years (117).

Kasperek *et al.* in a 2013 study of 111 neuromas reported excellent results in 44 patients, good results in 31, fair results in 15 and poor results in 8 following dorsal excision (93). They also showed that patients with more than one involved interspace had poorer outcomes, which in their study included such 11 cases. Many surgeons reserve the plantar approach for when a stump neuroma forms and requires excision (5). However, two recent studies that compared outcomes from the plantar and dorsal approaches reported no significant difference between the two methods (118, 119).

2.6.2.2 Neurolysis

The other surgical approach is to perform neurolysis, or ‘decompression’, of the affected nerve. Gauthier was the first surgeon to advocate release of the deep transverse metatarsal ligament to relieve symptoms associated with neuroma (47). He reported an 83% success rate in 304 patients treated with release of the transverse inter-metatarsal ligament without neurectomy. Release can be achieved via an open or endoscopic approach to sever the deep transverse metatarsal ligament. Okafor *et al.* in 1997 performed neurolysis by releasing the DTML and found that 17 of 35 patients enjoyed complete relief and 12 of 35 experienced minimal discomfort with activity after a mean follow up of 21 months (120). Villas *et al.* performed neurectomy or neurolysis on a group of 50 patients (69 feet) based on the criteria that neurectomy was performed in cases showing macroscopic thickening of the nerve (121). If no thickening of the nerve was observed, then the DTML was released together with any potential constrictive structures around the nerve (121). These authors reported good outcomes based on their selection criteria in both groups except for one patient. Consequently, they concluded that neurolysis responds well when obvious nerve thickening has not developed.

2.6.2.3 Lesser metatarsal osteotomies

In a retrospective study, Park *et al.* followed 86 consecutive patients of which 46 were treated with DTML release and the next 40 treated with DTML release and shortening osteotomy of the third metatarsal via a Weil osteotomy. Using The American Orthopedic Foot and Ankle Score (AOFAS) they concluded that metatarsal shortening osteotomy with DTML release resulted in better outcome compared to DTML release alone. They implemented this treatment based also on a cadaveric study by Kim *et al.* (50) showing that bifurcation of the nerve was distal to the DTML, hence questioning entrapment of the nerve by the DTML. Park *et al.* and Kim *et al.* popularized the theory that the main lesion of MN was located between the metatarsal head and the adjacent metatarsophalangeal (MTP) joint (see Figure 2.2) and hence shortening of the lesser metatarsal results in decompression of the nerve (10, 50).



Figure 2.2 Morton's neuroma after release of the deep transverse metatarsal ligament (DTML; dotted lines) (10)

The neuroma was located between the metatarsal head and the metatarsophalangeal joint and distal to the DTML (10).

Bauer *et al.* in 2015 also supported the hyper-pressure/trauma theory and stated that neurectomy, the current standard of care for management of MN, is not in keeping with this theory (18). He reported that 30% of his post-neurectomy patients were required to wear orthoses “because of persistent lateral metatarsalgia” (18). He advocated minimal incision surgery to perform metatarsal osteotomy with DTML release in order to manage patients with MN. He performed a retrospective study involving 52 patients, 25 of whom underwent traditional neurectomy and 25 underwent DTML release and metatarsal osteotomy using a percutaneous technique. The mean follow up period was four years. Using the AOFAS scoring system, he concluded his percutaneous technique provided “significantly better outcomes in the longer term and a lower rate of late metatarsalgia” than standard neurectomy (18).

Catani *et al.* in 2015 (112) also published results on percutaneous osteotomies for the treatment of MN using a similar technique to that of Bauer *et al.* He performed the procedure on 31 patients and claimed significant reduction in size of the MN as measured by ultrasound 6 months post-surgery. Of interest, 70% of the osteotomies were performed on the third metatarsal and Catani *et al.* claimed the success of the technique was achieved by “maintaining the transverse arch of the metatarsals” (18). Prior to this thesis work, no studies in the literature had reported on the relative length of lesser metatarsals in MN patients.

2.7 Methodology

This section comprises a literature review of the tools used for the measurements described in the following chapters. The three tools used are Foot Posture Index (FPI), Maestro technique and the EMED plantar measurement device.

2.7.1 Foot Posture Index© (FPI)

Foot posture index (FPI) was copyrighted to Anthony Redmond in August 2005 (122) and is a commonly used approach to quantify foot posture (123). FPI initially had 8 criteria (123) and was modified to 6 criteria for better reliability . The FPI categorises the degree of supination and pronation of the foot and is very easy to use. The six

criteria include talar head palpation, supra and infra lateral malleolar curvature, prominence of talo navicular joint, congruence of the medial longitudinal arch, abduction/adduction of the forefoot, and inversion/eversion of the calcaneus (Figure 2.3) (122). Each criterion is scored on a 5-point scale (-2 to +2), with positive numbers representing pronated foot posture and negative numbers supinated foot posture. This system has undergone numerous validation processes and has been extensively used in the literature to evaluate foot type (124-126).

2.7.1.1 Reliability and validity testing of FPI

The FPI-6 measurement tool has also been subjected to validity testing using Rasch analysis (127). This showed it had “good psychometric properties, good individual item fit, and good overall fit of the six criteria to the obtained model” (128). Cornwall *et al.* reported intra-rater reliability of the FPI as good, with an intra-correlation coefficient (ICC) of >0.90 (128) and considered to be a perfect result (129). The inter-rater reliability was only moderate however, with the highest ICC reported at 0.655 (128). Cain *et al.* in a study on the foot morphology of indoor football players found intra and inter-rater reliability with ICCs of 0.90 and 0.69, respectively (130).

Foot Posture Index Datasheet

Figure 1

	FACTOR	PLANE	SCORE 1		SCORE 2		SCORE 3	
			Date _____ Comment _____		Date _____ Comment _____		Date _____ Comment _____	
			Left (-2 to +2)	Right (-2 to +2)	Left (-2 to +2)	Right (-2 to +2)	Left (-2 to +2)	Right (-2 to +2)
Rearfoot	Talar head palpation	Transverse						
	Curves above and below lateral malleoli	Frontal/ transverse						
	Inversion/eversion of the calcaneus	Frontal						
Forefoot	Bulge in the region of the TNJ	Transverse						
	Congruence of the medial longitudinal arch	Sagittal						
	Abd/adduction of forefoot on rearfoot (too-many-toes)	Transverse						
Total								

Reference values

Normal = 0 to +5

Pronated = +6 to +9, Highly pronated 10+

Supinated = -1 to -4, Highly supinated -5 to -12

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www.leeds.ac.uk/medicine/FASTER/FPI.htm

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Figure 2.3 Six-item Foot Posture Index (122)

2.7.1.2 The relationship of FPI with dynamic motion

It is important to observe the relationship of static measurement such as FPI with dynamic measurements. Chuter studied and recruited 40 participants, half with normal feet and the other half with pronated feet as measured by FPI (131). Three dimensional rear foot motion was collected and correlated with FPI. The results of his study revealed that FPI had strong predictive ability for dynamic rear foot function. In another study involving 26 participants with patellofemoral pain syndrome and 20 controls, Barton *et al.* measured FPI and kinematic parameters of the forefoot and rearfoot using the three-dimensional motion analysis system (132). They concluded that a more pronated foot, as measured by FPI, was moderately associated with dynamic transverse plane abduction and rearfoot frontal plane eversion.

2.8 Radiographic Measurements

Radiographic measurements are especially important from a surgical point of view, since many techniques rely on radiographic measurements for peri-operative planning. However, there is no gold standard radiographic method for measuring metatarsal length. Of the several ways to measure metatarsal length radiographically, Morton's transverse lines and Hardy and Clapham's methods are the most commonly used diagnostic instruments (133). Other proposed measurement techniques include that of Maestro [161], which is the easiest to apply to all five metatarsals, along with a new but not yet validated method by Barroco *et al.* .

2.8.1 Maestro's method

This method was first described in 2003 with the aim of developing a pre-operative measurement and classification technique for the forefoot (Figure 2.4) . Maestro's original study was conducted using radiographs of 154 feet (134). Although the method of determining inter and intra-rater reliability was not clearly described, both were deemed to be "excellent" by the authors. However, questions regarding the reliability of this method have been raised. Deleu *et al.* conducted a radiographic study on 73 subjects (36 females and 37 males; mean age 30.4 ± 9.9 years) where two observers carried out the measurements on each foot of each patient and subsequently classified them according to Maestro's method (134). The reliability of classification between the two observers was then evaluated. A concordance of 92.6% for classification of the radiographic forefoot morphotypes was found between the two observers, thus Maestro's method was deemed precise and reproducible.

In contrast, a study by Chauhan *et al.* compared Maestro's method to those of Hardy, Clapham and Coughlin (133). Three months after recording the primary measurements, each observer repeated the measurements on a sample of 23 patients to assess intra-rater reliability. A further 23 patients were assessed in combination with previous data to evaluate inter-rater reliability. Both intra- and inter-rater errors were smallest

for the Coughlin method, largest for the Hardy and Clapham method and intermediate for Maestro .



Figure 2.4 Maestro's technique for measuring relative metatarsal lengths

Line 1 extends from the midpoint of the Chopart's joint to the distal apex of the second metatarsal head. Line 2 is perpendicular to Line 1 and bisects the fibular sesamoid and extends across the metatarsal heads. Lines 3-7 are perpendicular to Line 2, extending from the distal point of each metatarsal head.

2.9 Emed- x® Plantar Pressure Measurement Device

Plantar pressure measurement allows the assessment of high-pressure areas that many authors believe is a primary risk factor for plantar ulcers in diabetes and related pathologies (56, 135, 136). The Emed-x® force platform, a capacitance based system in which individual sensors are organised in a regular matrix, is an increasingly popular measurement device (137-139).

The Emed-x® system (software version 13.3.35) at the University of Western Australia Podiatry Clinic was used to measure the plantar pressure of 10 regions (masks) in individuals with MN and in control subjects. The system consists of a platform with dimensions of 700mm x 403mm x 15.5mm, with a calibrated capacitive sensor area of 475mm x 320mm composed of 6,090 individual sensors and with a resolution of 4 sensors/cm². The frequency of the system varies from 400-1000 Hz (61). The Emed system was used in the current study to compare peak plantar pressure measurements with various geometrical parameters in MN and control subjects.

2.9.1 Reliability of the Emed-x® system and plantar pressure measurements

Hafer *et al.* studied intra-mat, intra-manufacturer and inter-manufacturer consistency of plantar pressure parameters in addition to the number of trials needed to achieve stable results for two Emed-x® and two Tekscan MatScan devices in a single visit (137). All intra- and inter-platform reliabilities for Emed-x® were greater than 0.70. All parameters such as peak pressure, pressure time integrals and contact time for 10 regions of the foot reached a “value within 90% of the unbiased estimate of the mean within five trials” (137). Previous studies on older models of the Emed®-AT and Emed®-ST4 systems had also reported satisfactory reliabilities (140, 141).

2.9.2 Reliability of Emed-x® and geometric measurements

The use of geometric measurements during gait derived from an Emed-x® platform may provide clinicians and researchers with valuable information about the geometry and alignment of the foot. The geometrical parameters measured for this research were forefoot width, foot length, arch index, coefficient of spreading and foot progression angle (see Table 2.1 and Figure 2.5).



Figure 2.5 EMED generated geometric measurements during gait

AA' and BB' drawn from the medial and lateral aspects of the foot, respectively; OO' is formed by the bisection of AB and A'B'; P: point of contact of the tangent from A towards the heel; L: most lateral displacement of the medial midfoot border; N: point of contact of the tangent from L towards the forefoot; R: point of contact of the tangent from L towards the heel; C: point of contact of the tangent from A' to the hallux. All measurements are made from maximum pressure picture (142)

Table 2.1 Geometric measurement definitions (142)

Measurement	Definition
Foot length (FL)	Defined by placing a rectangle around the maximum pressure picture whose long side is parallel to the bisection of the long plantar angle. The length of the rectangle defines the foot length.
Forefoot width (FW)	Distance between the widest points of the ball of the foot (1st and 5th metatarsophalangeal joints).
Foot progression angle (FPA)	The angle between the axis (OO') and the vertical line parallel to the platform Y-axis. The vertical represents the direction of travel during data collection.
Arch index (AI)	The index is defined by the midfoot area divided by the total foot area (foot area minus toes area).
Coefficient of spreading (COS)	The forefoot width divided by the foot length.

Akins *et al.* in 2012 performed test-retest reliability of geometric measurements obtained during gait at a self-selected speed using a two-step approach (142). Data were collected on both feet for 10 healthy participants using the Emed®-X platform. Fifteen geometric measurements were demonstrated to be reliable with intra-class correlation coefficients (ICC) greater than 0.8, with 12 measurements ICC > 0.90. Specifically, excellent ICC's were reported for foot length (FL, 0.99), forefoot width (FW, 0.98), coefficient of spreading (COS, 0.92), arch index (AI, 0.97) and foot progression angle (FPA, 0.99).

2.9.3 Emed-x® platform automasking

A common method of investigating plantar pressures is to “mask” the foot into anatomical regions of interest to provide more clinically relevant information than observation of the foot as a whole (143, 144). The Novel® Multi mask software (Novel GmbH Munich, Germany) provides the ability to “automask” the foot into the chosen number of regions. Specific plantar pressure variables may be computed for each individual mask or region. Such automasks have been applied to analyse the plantar pressures pre- and post-surgical reconstruction (145, 146), for normal walking parameters (139, 147) and for various foot deformities (56, 59).

Ellis *et al.* in 2010 studied the accuracy of the Emed-x® platform using the Novel® ten-region standard automask system (138). They reported the average accuracies of the automasking algorithm regions for dynamic measurements were 98.8% for the first metatarsal, 89.9% for the second, 98.6% for the third, 96.8% for the fourth and 93.1% for the fifth.

2.9.4 Factors influencing plantar pressure distribution

Demographic characteristics such as body-weight, age and gender have been investigated for their effect on plantar pressure measurements. Hills *et al.* in 2001 studied the effect of obesity on plantar pressure measurements (148). “Obese” was defined as a BMI of greater than 30. The study was conducted on 35 males (age 42.4±10.8 yrs; 67-179 kg) and 35 females (age 40.0±12.6 yrs; 46-150 kg) using

Emed-x®. Obese subjects showed increased forefoot width during standing and walking and higher plantar pressures of the metatarsal heads and longitudinal arch areas. Murphy *et al.* reported that an average male has a greater normalised contact area and higher plantar pressure values compared to females, however this difference was not significant (149). Hills *et al.* also reported that obese female subjects had higher forefoot and mid-foot pressures during standing, possibly due to ligamentous laxity, however this difference was not observed dynamically (148). Using an Emed platform, Kernozek and LaMott compared plantar pressure measurements of 35 elderly subjects (71-95 years) with 35 younger subjects (18-24 years) (150). They found an increased medial loading but no difference in central forefoot pressures with age. In older subjects (>70 yrs) it has also been reported that foot pressure distribution decreases in magnitude under the heel, lateral forefoot and hallux, but there is longer contact under the heel, midfoot and metatarsal phalangeal joints (151).

Taylor *et al.* studied the effect of walking speed (slow, normal and fast) in 20 healthy participants (10 males, 10 females) aged 20–37 years (mean 27.5 yrs, S.D. 5.2 yrs) with an Emed-SF system and using the two-step gait initiation protocol (152). They found no significant differences between self-selected slow and normal speeds for maximum force and peak pressure values. With increased walking speeds, contact time increased at all regions under the foot.

The plantar pressure measurements can be affected by foot type and foot deformities. Using an Emed-SF® system, Burns *et al.* studied 30 subjects with idiopathic cavus foot, 10 with neurogenic cavus foot and 30 normal subjects (153). The pressure time integrals in the rear foot and forefoot in both cavus foot groups were higher than in the normal group. Other studies have shown that subjects with hallux valgus, toe deformities, diabetes with neuropathy, leprosy and rheumatoid arthritis can display altered plantar pressures in the forefoot (56, 136, 154-156). Accordingly, subjects with other forefoot complaints such as bunions, hammertoes, plantar plate pathology, systematic arthritis and diabetes have not been included in the current research project.

2.9.5 Method of data collection

A midgait method is usually used for the collection of pressure data (144). The dimensions of pressure distribution platforms are typically small and the plates are difficult to target with the foot during the midgait method of data acquisition (139, 144, 157). Patients with foot pathology may have difficulty managing a midgait technique. Because of the practical difficulties involved with the mid-gait measurement technique, a number of researchers have investigated the reliability of measurement taking less steps in the data acquisition process.

Bryant *et al.* studied the reliability of plantar pressure measurements acquired using the traditional midgait method compared to the two-step method (139). They used the Emed-SF[®] system and investigated the parameters of contact area, contact time, maximum force and peak pressure at 7 sites of the foot for reliability of measurement in 10 normal subjects. They concluded the two-step method is as reliable as the midgait method and may be ideal for use in both research and clinical practice. Other investigators have also supported the two-step gait technique (157, 158).

2.9.6 Normal plantar pressure measurements

In a previous study by Bryant *et al.* (147) with respect to peak pressure (PP) distribution on 10 masked areas, the maximum mean values were found under the heel, the second and third metatarsal heads, and the hallux. The least variation of plantar pressure (mean and peak pressures) was found under the heel, second and third metatarsals. The greatest variations were found under the toes and midfoot. This may be due to variability in arch heights, as other studies have confirmed this variation (159).

Kanatli *et al.* studied plantar pressure distribution under the forefoot of 106 healthy subjects using an Emed-SF[®] system (160). They masked the foot into medial column (first metatarsal), middle column (second and third metatarsals) and lateral column (fourth and fifth metatarsals). They found that during midstance and the push-off phase of gait, the mean and peak pressures were highest under the second and third metatarsals. Their study questioned the existence of the transverse metatarsal arch

during gait. The absence of the transverse metatarsal arch was supported in their previous study where they showed the transverse arch collapses during the push-off phase (161). This questions the tripod theory proposed by Kapandji *et al.* which states that the longitudinal and transverse arches of the foot result in weight-bearing like a tripod between heel, first and fifth metatarsals (162). Other investigators have questioned the presence of the transverse arch using ultrasonography on 100 healthy subjects and measuring their plantar pressures of the forefoot using an Emed-SF[®] system (163). Using ultrasound measurements in the weight bearing position, they found the second to fourth metatarsal heads to be in a more plantar position and the maximum plantar pressure measured by an Emed-SF[®] system to be present in the third metatarsal head region.

With respect to pressure time integrals (PTI), Bryant *et al.* reported the highest measurements were under the second and third metatarsal heads and the hallux, and the greatest variation was noted under the fifth metatarsal head and toes (147).

Chapter 3. Description of Hospital Admissions of Morton's Metatarsalgia in Australia

Adapted from: **Naraghi R**, Bryant A, Slack-Smith L (2014) Description of total population hospital admissions for Morton's metatarsalgia in Australia. *J Am Podiatr Med Assoc.* 104;451-4

3.0 Rationale of the Study

MN (also known as Morton's metatarsalgia, interdigital neuritis, and neuralgia) is a painful condition in the plantar aspect of the forefoot attributed to thickening and fibrosis of the common digital nerve at the level of the bifurcation into common digital branches (19, 63). Footwear seems to play a role in the formation of Morton's metatarsalgia in susceptible individuals (44, 164), and the condition is said to affect mostly women who wear high-heeled shoes (44, 164). The literature indicates that it is more common in women, but men are also affected by this malady (3, 19, 63).

There is a dearth of epidemiological data regarding hospital admissions for Morton's metatarsalgia internationally. The purpose of this chapter is to describe the epidemiology of hospital admissions for MN in Australia, including the description of admissions by patient sex and age group, using International Classification of Diseases, 10th Revision (ICD-10) diagnosis codes.

3.1 Methods

We extracted data on MN admission to public and private hospitals across all Australian states and territories from the Australian Institute of Health and Welfare online database from 1998 to 2008 (165). Individual-level data were not available. The data have been recorded based on standardized International Statistical Classification of Diseases and Related Health Problems, 10th Revision, Australian Modification (ICD-10) (166). The ICD-10 code of G57.6 corresponds to Morton's metatarsalgia or MN. The factors extracted from the online data were total number of admissions, age,

sex, and age groups of patients admitted with an ICD-10 code of G57.6. The male-to-female ratio and percentage of admissions within each age group were determined.

The ICD-10 code G57.6 was used to allow the investigators to look at admissions for this disorder using the Australian Institute of Health and Welfare (AIHW) data (165). The AIHW is an Australian Government organisation that provides information and statistics on Australian health and welfare matters.

Estimated resident population counts of all sociodemographic stratifications for 1998 to 2008 were available from the Australian Bureau of Statistics (167). Rates were generated by dividing the number of hospital admissions of MN by the estimated resident population of the same specified group and multiplying by 100,000 to determine the number of hospital admissions per 100,000 people per year. The rates for 3 years (1998, 2001, and 2004) were calculated to observe the variation over time. The standard error formula for rates was used to derive standard errors and consequent 95% confidence intervals. Findings were considered significant at the $P < 0.05$ level (168). We used publicly available raw data and received approval for this project from the Human Research Ethics Committee of the University of Western Australia.

3.2 Results

There were 13,579 hospital admissions with a diagnosis of MN from 1998 to 2008 (Table 3.1); 3,266 patients were male and 10,313 were female. The average female-to-male ratio was 3.2 to 1.0. The highest rates of admission for MN among women were in the 50- to 54-year-old age group; for men, the highest admission rates were in the 55- to 59-year-old age group (Figure 3.1). The highest rate for women was in 2001 at 10.92 and for men in 1998 at 4.01 per 100,000 populations per year (Table 3.2). Over the period reviewed, the highest overall rate for the total population study from 1998 to 2008 occurred in 1998 at 7.43 per 100,000 population. The rates for every age group for the years 1998, 2001, and 2004 were determined (Table 3.1). The highest rate in 1998 was in the 55- to 59-year-old age category at 22.10 per 100,000; in

2001, the highest rate was in the 60- to 64-year-old category at 23.60 per 100,000; and in 2004, the highest rate was in the 55- to 59-year-old age category at 21.54 per 100,000. The rates for each of these 3 years varied slightly; however, the female-to-male ratio remained constant at approximately 3 to 1.

Table 3.1 Total number of admissions, percentage of admissions and the rates per year per 100,000 population for the years 1998, 2001 and 2004

Age Group	Total Admissions (1998–2008)	Total % Admissions	Rate 1998	Rate 2001	Rate 2004	Mean Rate	95% CI
1–19	62	0.45	1.41	0.00	0.22	0.54	0.00– 2.03
20–24	157	1.16	2.34	1.46	0.57	1.46	0.00– 3.19
25–29	345	2.54	3.69	2.84	1.99	2.84	1.17– 4.50
30–34	603	4.44	4.39	6.34	3.41	4.71	1.79– 7.64
35–39	1,031	7.59	7.81	8.11	6.01	7.31	5.08– 9.53
40–44	1,204	8.87	9.02	8.31	6.35	7.89	5.18–10.61
45–49	1,660	12.22	12.68	13.32	11.97	12.66	11.33–13.99
50–54	2,267	16.69	20.01	18.53	14.90	17.81	12.67–22.96
55–59	2,258	16.63	22.10	19.53	21.54	21.05	18.41–23.70
60–64	1,743	12.84	19.48	23.60	19.70	20.93	16.38–25.47
65–69	1,075	7.92	17.68	12.75	17.18	15.87	10.55–21.19
70–74	672	4.95	12.75	9.24	9.90	10.63	6.97–14.29
75–79	338	2.49	6.60	8.86	6.98	7.48	5.11– 9.85
80–84	140	1.03	4.10	4.85	4.44	4.46	3.73– 5.20
85+	24	0.18	0.44	0.75	1.38	0.86	0.09– 1.63
Male	3,266	24.05					
Female	10,313	75.95					
Total	13,579	100					

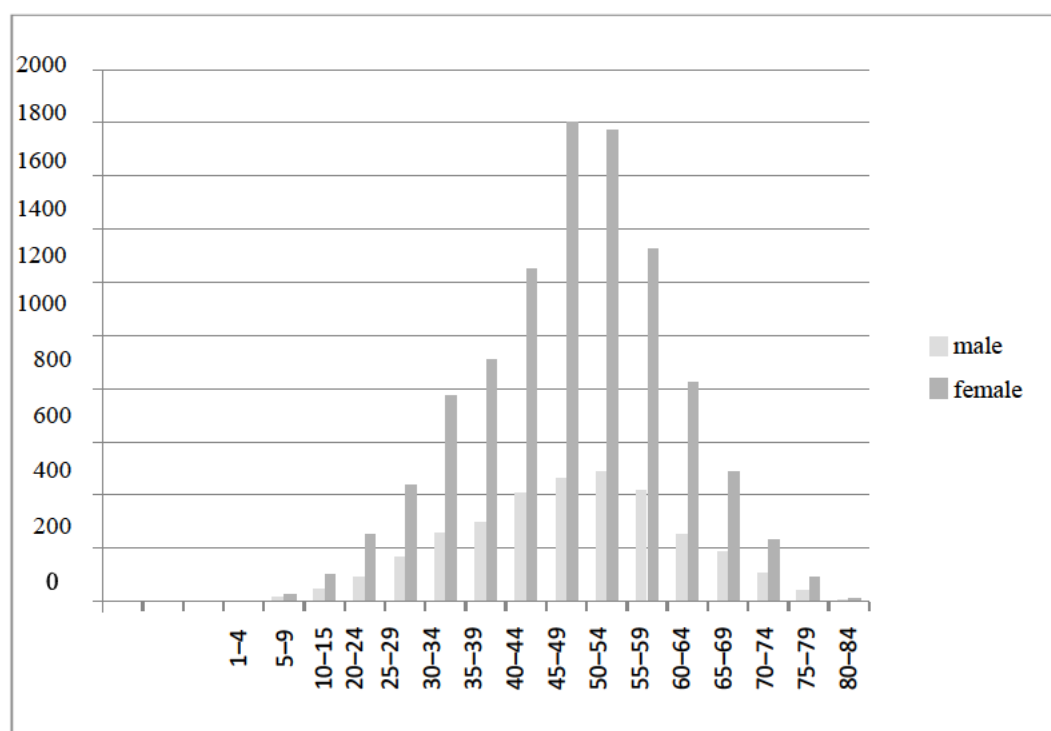


Figure 3.1 Age group in years (male and female) and total number of admissions

Table 3.2 Rates for 1998–2008 Male and Female (admissions per 100,000 per yr)

Years ^a	1998–	1999–	2000–	2001–	2002–	2003–	2004–	2005–	2006–	2007–
	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008
Rates, male	4.01	3.32	3.40	3.63	3.37	3.01	2.93	2.84	3.46	3.24
Rates, female	10.81	10.06	10.46	10.92	9.90	9.64	10.65	10.13	10.38	10.47
Total	7.43	6.71	6.89	7.30	6.66	6.36	6.82	6.51	6.94	6.88

^a Australian financial year 1 July to 30 June.

3.3 Discussion

Although a number of studies have investigated the outcome of surgery on patients with MN, previous studies have not used population data. Bradley *et al.* (169) found that of 85 individuals who underwent surgery for MN, 71 were females and 14 were males (ratio of 5 to 1). In a 1979 study, Gauthier (47) sectioned the deep transverse intermetatarsal ligament of 206 individuals, with a female to male ratio of approximately 10 to 1 (187 females and 19 males). Other ratios of females to males who underwent surgery for Morton's metatarsalgia have been reported in the literature (47, 64, 169), however no study to date has reviewed large sample sizes that reflect the entire general population of a particular country.

In 2006, Latinovic *et al.* (43) studied data on the incidence of common compressive neuropathies from 253 general medical practices across the United Kingdom. Morton's metatarsalgia was found to be more common in women and in both men and women between the ages of 55 to 64 years, thus similar to the current findings; the male-to-female ratio was 1.8 to 1.0. They also studied the rate of operative treatment and found a female-to-male ratio of 2.3 to 1.0, which is also similar to the present results. However, their study was based on general practitioner medical practices spread across the United Kingdom and hence this does not necessarily resemble the total population. In an earlier study using MBS item numbers, 11,037 neurectomies were performed in Australia from 1997 to 2006 (170). These were most frequent in the 55 to 64 age group, which is also similar to the present findings.

This research has analysed total population data in Australia for Morton's metatarsalgia using the Australian Institute of Health and Welfare databases of hospital morbidity from 1998 to 2008. Such data are useful for morbidity and cost estimates. Although somewhat complex to access and manage, these data are publically available and can be used to follow trends for this disorder. The study reflects the rate of hospital admissions (both public and private) for the surgical management of MN by podiatric and orthopedic surgeons. However, it did not capture patients diagnosed with MN in

private or public clinics and hence does not reflect the true population incidence and is likely to underestimate total morbidity.

The results show that the rate of hospital admission for Morton's metatarsalgia is three times higher in women than men and that the highest admission rate occurs in 50-55 yr olds at 10.9 cases per 100,000 population.

Chapter 4. The Relationship between Foot Posture Index, Ankle Equinus, Body Mass Index and Morton's Neuroma: A Case-Control Study

Adapted from: **Naraghi R**, Bremner A, Slack-Smith L, & Bryant A (2016) The relationship between foot posture index, ankle equinus, body mass index and intermetatarsal neuroma. *Journal of Foot and Ankle Research* 9:46

4.0 Rationale of the Study

Numerous aetiologies have been postulated in the literature for MN, including pronation (1, 7, 63), metatarsus proximus [15,16], trauma (5), ankle equinus (13, 14, 59, 171, 172), bursitis (5, 69, 115), entrapment by the deep transverse metatarsal ligament (5, 47), and anatomical variations such as presence of the communicating branch of the lateral plantar nerve (1, 32, 33). Jarde reported that flatfoot was associated with the development of MN in 44% of a 43 patient series (65). Hagedorn *et al.* in a 2013 study of 3,429 participants reported associations between foot posture and common foot problems such as hallux abducto valgus, hammertoe, overlapping toe, hallux rigidus and MN (173). Foot posture was recorded using a foot arch index and foot function was assessed using the Centre of Pressure Excursion Index via a TekscanTm pressure mat. Centre of Pressure Excursion Index was utilised as a dynamic measurement to identify feet as either over-pronated, neutral or over-supinated. Their results showed no association between MN (n=439) and any foot posture and function. However, their study did not compare the foot posture of subjects with foot disorders with that of control subjects.

Excessive pronation can lead to hypermobility of the metatarsal heads and it has been postulated that movement between the fixed medial column and the more mobile lateral column of the foot can place excessive pressure on the third interspace nerve (1, 11, 63, 65, 115, 174). This, along with the traction caused by the flexor digitorum brevis has been implicated as a possible cause of the formation of MN in the third

interspace (63). It has been suggested that MN in the second interspace is more common in the neutral to cavus foot due to the close proximity of the second and third metatarsal heads . This tight space predisposes the nerve to compression by the bursa above the nerve and the lumbricalis muscle/tendon arising from the medial aspect of the flexor digitorum longus that runs parallel to the nerve (175). Furthermore, the plantar declination of the metatarsals in a cavus foot type can increase pressure over the corresponding nerve (67). Pazzaglia *et al.* reported that 75% of MN patients (n=12) in their study had a cavus foot type with forefoot deformity (8). To date, there are no case-control studies in the literature that investigate the association of MN with foot posture. Additionally, a mechanism that relates foot posture to the occurrence of MN in the second and third interspaces has not yet been proposed. Therefore, in the the present study we hypothesized that the occurrence of MN in the third interspace is associated with a pronated foot posture, while the occurrence of MN in the second interspace is present in a more neutral to supinated foot type.

To accurately evaluate the association of foot posture with MN, investigators can use a simple and efficient tool such as The Foot Posture Index TM (FPI). FPI is regularly used by clinicians to assess foot type prior to implementing orthotic therapy (126). The FPI measurement tool has also been validated using Rasch analysis, which concluded that it had “good psychometric properties, good individual item fit, and good overall fit of the six criteria to the obtained model” (127). In addition, Cornwall *et al.* showed that FPI had high intra-rater reliability, with intraclass correlation coefficient (ICC) levels >0.9. However, inter-rater reliability with ICC values were moderate and ranged from 0.525 to 0.655 . Although there is no available literature that has investigated FPI and MN, this tool is frequently employed for studies of association between foot type and many other lower extremity conditions (132, 176, 177).

Reduced ankle joint dorsiflexion, also known as ankle equinus, is surmised to cause MN (12-14, 172, 178). A lack of adequate ankle dorsiflexion can result in compensation during gait, such as an early heel lift and an increase in forefoot pressures (171), thus causing pain in the forefoot (172). Measurement of ankle joint dorsiflexion is used frequently by clinicians in their day to day practice. There is

limited high quality evidence to support the relationship between ankle joint range of motion and MN, with only one case study reporting an improvement in forefoot nerve symptoms following a gastrocnemius release (12).

The current study investigates for possible associations between foot type (as measured by FPI), ankle equinus and body mass index (BMI) as predisposing factors for MN. It also examines the relationship between foot type and the affected interspace with MN.

4.1 Methods

Cases and controls were recruited from patients attending The University of Western Australia (UWA) Podiatry Clinic. The inclusion criteria for MN subjects included:

- A minimum of six-month history of pain in an affected interspace and a clinically demonstrated positive painful Mulder's click
- A positive ultrasound and/or MRI evidence of MN in the affected interspace

The inclusion criterion for control subjects was:

- No history of MN or neuroma-like pain in the forefoot

The exclusion criteria for both neuroma and control groups were:

- A previous history of surgery to the lower extremity
- Any proximal nerve entrapment at the level of the ankle, knee, hip or back
- Any history of significant trauma to the forefoot area
- Any difficulty in walking and standing
- Diabetes or a history of systemic arthritis
- Bony ankle and soleus equinus

In this study we did not attempt to match the cases and controls. According to Pearce, matching in a case-control study “does not control for confounding by the matching factors; in fact it can introduce confounding by the matching factors even when it did not exist in the source population” (179). In this research we were looking at possible

casual effect between the cases and controls and hence an unmatched design was preferred.

4.1.1 Recruitment

Approval for this study was obtained from the University of Western Australia Human Research Ethics Committee. A total of 100 participants were recruited from the UWA Podiatry Clinic, 68 of whom were diagnosed with MN from 2009-2015. There were 32 control participants recruited from 2014-2015. All participants provided a medical history and underwent a physical examination by a practicing podiatrist.

4.1.2 Measurements

The age, weight and height of all subjects was recorded and their BMIs calculated. The FPI was measured according to the FPI User Guide Manual (122) by the same podiatrist with more than 10 years experience in clinical practice. Measurements were taken twice and the average value recorded. Ankle dorsiflexion was measured for each subject with a goniometer using the technique described by Root *et al.* (180). The subtalar joint was placed in neutral with the patient in a prone position and the ankle dorsiflexed passively while maintaining subtalar joint neutral position. The subject was then asked to actively dorsiflex the foot while the examiner maintained the subtalar joint in a neutral position. The angle formed between the lateral rear foot and the lateral bisection of the distal 1/3 of the fibula was measured. Two measurements were taken and the average recorded. The intra-rater reliability of the ankle dorsiflexion measurements was tested by using the measurements from 8 subjects performed three times to calculate the ICC using a two-way mixed effects model in IBM SPSS Statistics v22 (IBM Corp, Armonk, NY, USA). The ICC of 0.95 (95% CI 0.83-0.99) indicated that intra-rater reliability was good.

4.1.3 Statistical Analysis

IBM SPSS Statistics v22 was used for analyses. The significance level was set at 0.05. Results are expressed as mean $\pm$ SD. Medians and ranges are also presented for

non-normally distributed measures. Independent sample *t*-tests were used to compare the mean age, BMI, FPI and ankle dorsiflexion between MN and control groups. In addition, Kruskal-Wallis tests were performed to test for differences in foot type and ankle dorsiflexion between the interspaces affected. Chi-square tests were used to determine whether there was any association between the interspace(s) and the foot (feet) affected in MN subjects, and whether the proportions of males and females with ankle dorsiflexions less than 10 degrees differed. Associations were also investigated using multivariable logistic regression. Odds ratios (ORs) and 95% confidence intervals (CIs) are reported.

4.2 Results

The 68 MN cases had a mean age of 52 ± 14 years (range 20 to 74 years) and comprised 56 females and 12 males. The control group of 32 subjects had a mean age of 49 ± 10 years (range 24 to 67 years), with 26 females and six males. There were no significant differences in age between the MN and control groups ($p=0.28$), or BMI between the MN (26.9 ± 5.7) and control (26.5 ± 4.1) groups ($p=0.72$). Approximately equal percentages of all men and women in the study had MNs: 66.7% of men and 68.3% of women ($p=0.89$).

Figure 4.1 shows the FPI scores for the MN and control groups. The mean FPI scores were 3.5 ± 2.9 (range, -5 to 8) for right-foot MN and 2.9 ± 2.8 (range, -1 to 7) for left-foot MN (Table 4.1). The control group mean FPI score for the right foot was 2.7 ± 2.5 (range, -3 to 7) and for the left foot 3.0 ± 2.9 (range, -5 to 8). There were no significant differences in the mean FPI scores for the right and left feet between cases and controls ($p= 0.21$ and 0.87 , respectively). There were, however, significant differences in mean ankle dorsiflexion between the MN and control groups ($p<0.001$ for both feet). The ankle dorsiflexion measurements of MN subjects were 5.91 degrees lower (95% CI: 4.04-7.78) for the right foot and 7.34 degrees lower (95% CI 5.55-9.13) for the left foot. Figure 4.2 shows the ankle dorsiflexions of the MN and control groups. Male and female ankle dorsiflexion measurements did not differ significantly, nor did the proportions of male and female MN subjects with ankle dorsiflexion less than 10

degrees. These were 87.5% versus 75.0% on the right ($p=0.66$), and 75.0% versus 86.7% on the left ($p=0.59$) for males and females, respectively.

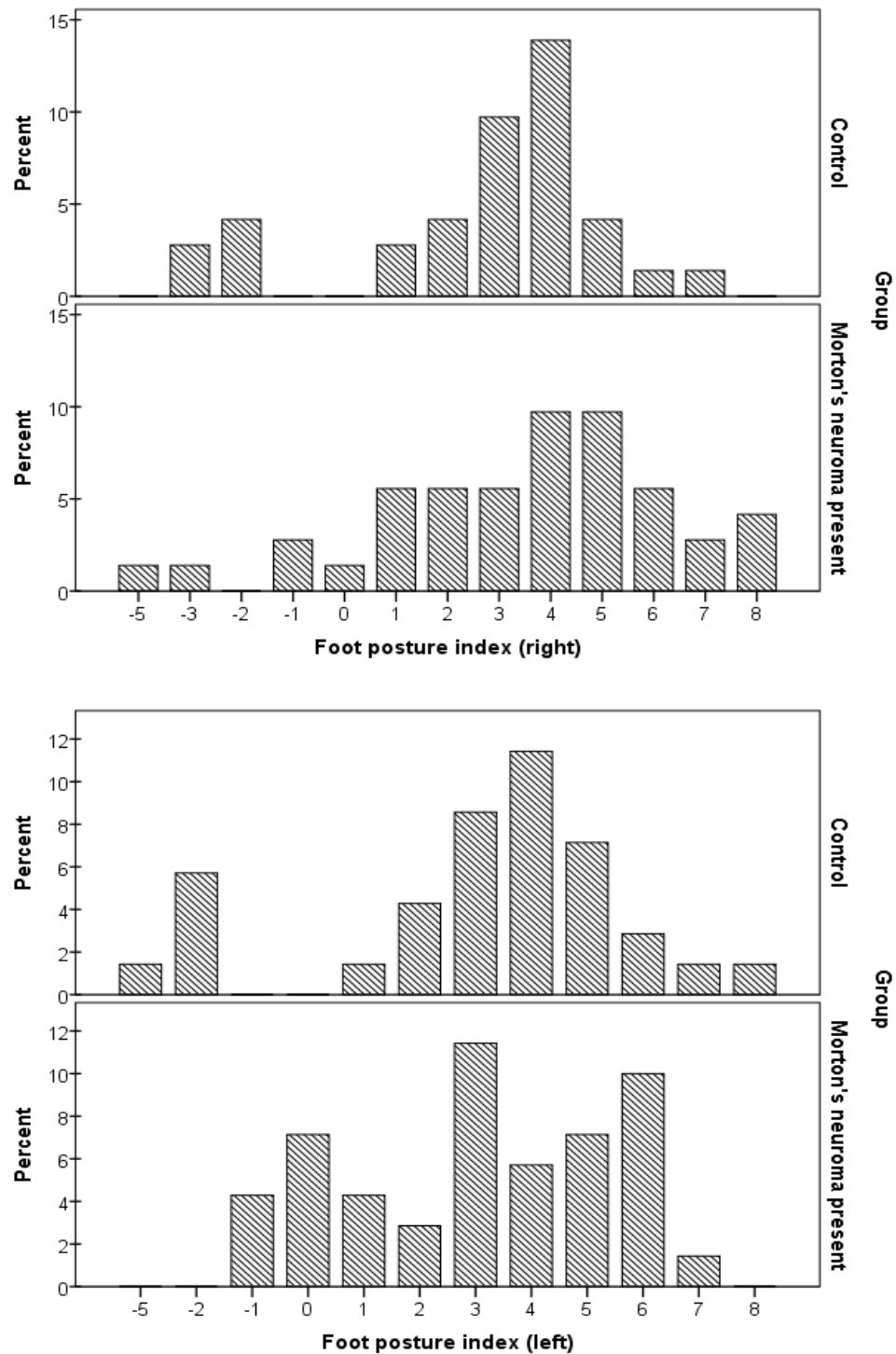


Figure 4.1 Graph of foot posture index for intermetatarsal neuroma and control groups – left and right feet

Table 4.1 Comparison of characteristics between Morton's neuroma and control groups by affected foot

		Case (IMN present) <i>n</i> = 68		Control (No IMN) <i>n</i> = 32		P-value
		Mean ± SD	Range	Mean ± SD	Range	
MN right foot <i>n</i> = 40	FPI	3.5 ± 2.9	−5 to 8	2.7 ± 2.5	−3 to 7	0.210
	ADF	5.3 ± 3.9	0 to 15	10.9 ± 3.6	0 to 20	<0.001
MN left foot <i>n</i> = 38	FPI	2.9 ± 2.8	−1 to 7	3.0 ± 2.9	−5 to 8	0.870
	ADF	4.1 ± 3.9	0 to 15	11.3 ± 3.1	2 to 18	<0.001

MN Morton's neuroma, FPI Foot Posture Index, ADF Ankle dorsiflexion (degrees). P-values from independent *t*-test comparison of cases with controls. Note: there is some overlap in cases as some subjects have MN in both feet.

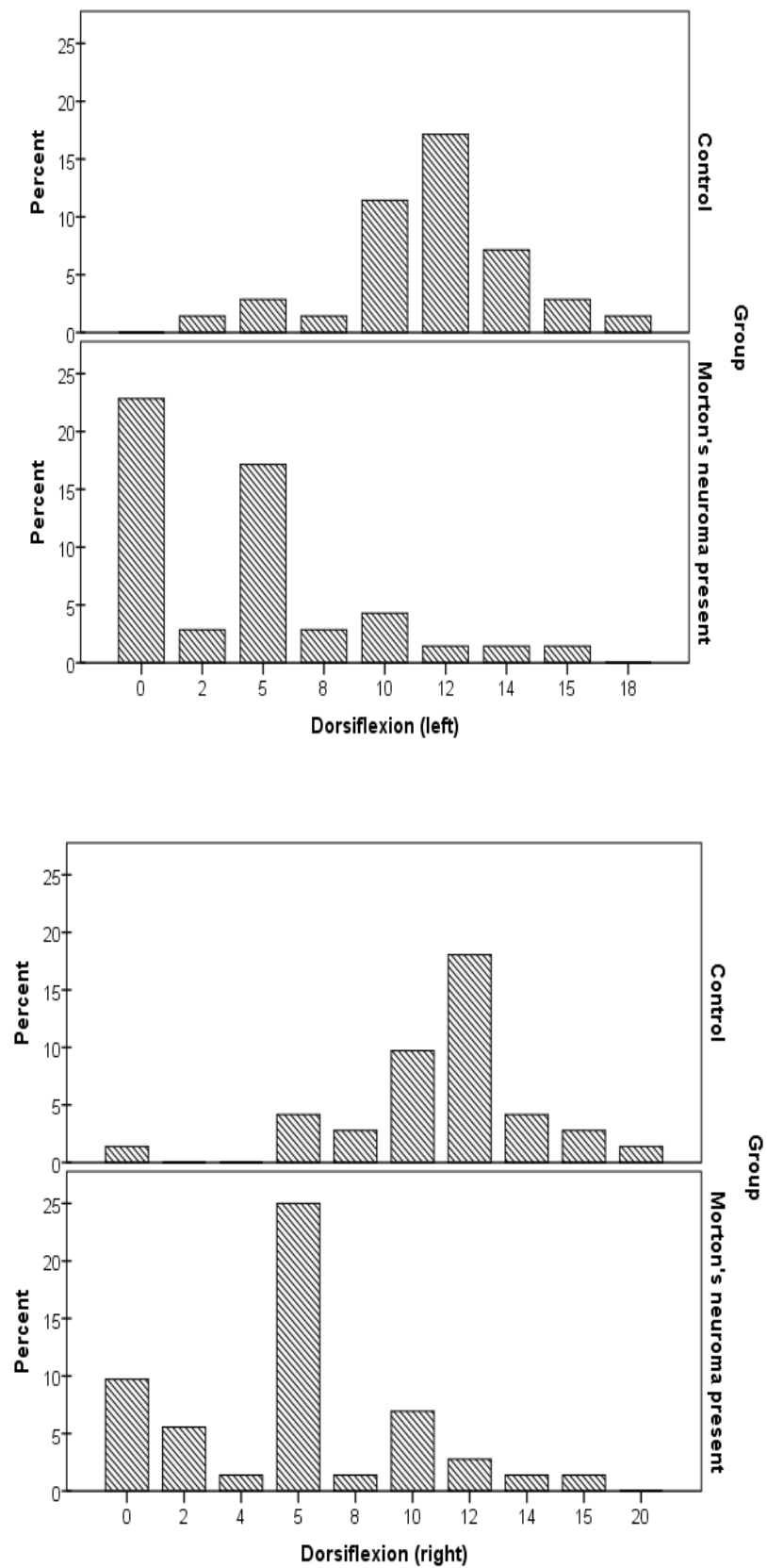


Figure 4.2 Graph of ankle dorsiflexion in degrees for Morton's neuroma and control groups—left and right feet

Of the MN subjects, 28 were diagnosed with MN in the second interspace, 23 in the third interspace and 17 in both the second and third interspaces. Three subjects had MN of the second and third interspaces in both feet (Table 4.2). There was no significant association between the interspace(s) affected and the foot (feet) affected with MN(s) ($p=0.16$).

Table 4.2 Description of Morton's neuroma by foot and the interspace(s)

Interspace	affected			
	Right Foot	Left Foot	Both Feet	Total
2/3	14	9	5	28 (41.2%)
3/4	12	8	3	23 (33.8%)
Both	3	11	3	17 (25.0%)
Total	29 (42.6%)	28 (41.2%)	11 (16.2%)	68

Total interspaces affected: right foot (n=40); left foot (n=38)

To evaluate the relationship between FPI and affected interspaces, we divided MN subjects according to their affected interspace and compared them with controls. The second interspace FPI means were 3.2 ± 2.6 and 2.7 ± 1.9 on the right (n=19) and left (n=13) feet, respectively. The third interspace FPI means were 3.20 ± 3.5 and 2.9 ± 2.8 on the right (n=15) and left (n=11) feet, respectively (Table 4.3). FPI did not differ significantly across groups when MN subjects were divided according to their affected interspace(s) ($p=0.27$ on the right and $p=0.47$ on the left), nor did ankle dorsiflexion differ across interspace groups ($p=0.80$ on the right and $p=0.79$ on the left). Logistic regression models, adjusted for age, sex, FPI and BMI, estimated that the odds of having MN in the right foot decreased by 38% (OR 0.62; 95% CI: 0.51-0.76) with each additional degree of ankle dorsiflexion, and in the left foot by 30% (OR 0.70; 95% CI: 0.59-0.82) (Table 4.4).

Table 4.3 The relationship between affected interspaces, foot posture index and ankle dorsiflexion

		Right Foot		Left Foot	
IP	n	FPI	ADF	FPI	ADF
		mean±SD	mean±SD	mean±SD	mean±SD
		median	median	median	median
		median (range)	median (range)	median (range)	median (range)
2/3	1	3.2±2.6	4.63±2.87	13	2.7±1.9
	9	4 (−3 to 7)	5 (0 to 12)		3 (0 to 5)
3/4	1	3.2±3.5	5.87±4.66	11	2.9±2.8
	5	3 (−5 to 8)	5 (0 to 14)		3 (−1 to 7)
Both	6	5.2±1.7	6.17±5.49	14	3.6±2.5
		5 (3 to 8)	5 (0 to 15)		4 (−1 to 6)
P-value		0.27	0.80		0.47

IP, interspace, p-value from Kruskal-Wallis one way analysis of variance test (non-parametric test).

Table 4.4 Multivariable logistic regression estimates of odds of one or two Morton neuromas

		Right Foot		Left Foot	
Variable		OR (95% CI)	P-value	OR (95% CI)	P-value
Age (years)		1.06 (0.99,1.14)	0.75	0.99 (0.94, 1.04)	0.75
BMI (kg/m2)		0.88 (0.73, 1.06)	0.20	1.09 (0.96, 1.24)	0.20
Female ¹		2.08 (0.34, 12.8)	0.95	0.96 (0.23, 4.03)	0.95
FPI		1.29 (0.93, 1.81)	0.85	1.02 (0.82, 1.27)	0.85
ADF (degrees)		0.62 (0.51, 0.76)	<0.001	0.70 (0.59, 0.82)	<0.001

BMI Body mass index. FPI Foot Posture index. ADF Ankle dorsiflexion (degrees). OR Odds ratio. CI Confidence interval. ¹ Compared to male. Other ORs are per unit increase.

In summary, no significant differences in FPI were apparent between affected MN interspaces, or between cases and controls. MN subjects had significant lower ankle dorsiflexion measurements compared with control subjects.

4.3 Discussion

This study found no association between foot posture according to the FPI and MN formation. The mean FPI values measured here were slightly less than the normative value of +4 reported by Redmond *et al* after measuring FPI in 619 healthy subjects (181). The mean FPI scores in the present study for right-foot MN (mean 3.5 ± 2.9 ; range, -5 to 8) and left-foot MN (mean 2.9 ± 2.8 ; range, -1 to 7) were not significantly different to the controls ($p=0.21$ and $p=0.87$, respectively). In the Framingham population study, Hagedorn *et al.* also did not find a significant association between foot posture and MN (173).

Most of the literature states that the third interspace is more commonly affected with MN due to anatomical and biomechanical reasons (5, 8, 19, 63, 175). Keh *et al.* (9) reported a slightly increased occurrence of MN in the second interspace, but an equal distribution of MN in both interspaces was reported by Mann *et al.* (45). In the present study, approximately 41% of MN occurred in the second interspace, 34% in the third interspace and 25% in both interspaces (Table 4.3). No relationship was found between FPI and MN in any particular interspace. Therefore, our hypothesis that MN occurs more commonly in the third interspace in a more pronated foot resulting from hypermobility of the lateral column relative to the medial column was not supported by these findings. Furthermore, even though the second interspace was the most frequently affected site, cavus foot posture was not associated with formation of MN in the second interspace.

It is reasonable to assume that individuals with a high BMI would have increased pressure in the forefoot during the propulsive phase of gait, which may traumatize plantar interspace nerves. However, in the current study no significant difference in mean BMI was observed between the MN and control groups. The Johnston County

study reported there was no clear association between BMI and the presence of foot deformities (182). However, in a systematic review by Butterworth *et al.*, a significant association between foot pain as a result of non-specific foot disorders and increasing BMI was reported (183). Obesity has been linked to an increase in plantar pressure measurements, which lead to a more pronated foot and increase in foot pain (184, 185). In our case-control series, no relationship between BMI and MN formation was established.

A number of authors state that a lack of ankle dorsiflexion in gait increases pressure of the forefoot (12, 14, 54, 171, 178). Barrett and Jarvis went as far as to recommend endoscopic gastrocnemius release as a treatment for MN patients exhibiting ankle equinus (12). DiGiovanni *et al.* studied the effect of isolated gastrocnemius tightness in a group of 34 patients with forefoot and midfoot pain versus a control group of 34 subjects with no foot or ankle pain. These authors used an equinometer to measure ankle dorsiflexion and defined equinus as less than 5 degrees. They found a twofold higher rate of equinus in the patient group compared to the control group. However, their study did not include any patients with MN and only 7 subjects were diagnosed with metatarsalgia of non-neurological origin. Fryberg *et al.* reported a three-fold increase in equinus in a diabetic group compared to a non-diabetic group of subjects (186). Due to peripheral neuropathies, diabetics are more predisposed to equinus deformity which can lead to an increase in forefoot pressure and hence ulcerations (54, 186). Even though diabetes was one of the exclusion criteria in the present study, the results indicated a marked decrease in ankle dorsiflexion in MN subjects compared to control subjects (Tables 4.1 and 4.4 and Figure 4.2). Although the measurement technique used here has been reported in the literature as unreliable (187, 188), the intra-rater reliability was found to be high.

Another mechanism by which ankle equinus exerts its pathological forces is best explained by the “split second effect” (52). The human gait constitutes a three rocker mechanism: heel rocker, ankle rocker and forefoot rocker (60). The split second effect is the span of time during which the effect of pathological forces exerted on the foot initiates in the second half of the ankle rocker to the end of the forefoot rocker (52).

When there is lack of ankle dorsiflexion, the forces exerted on the foot exponentially increase as “gastrocnemius prematurely reaches its endpoint” (52). Two type of forces are created by the split second effect. Direct tension forces occur in the posterior muscle group complex and plantar fascia. Indirect forces are a result of the ankle and forefoot rocker mechanism exerted on the forefoot as the proximal limb progresses over the foot. This increase in activation of windlass can lead to increased strain on plantar fascia (189) and place all of the soft tissue structures surrounding and including the plantar nerve under stretch and strain. The collapse of the transverse arch places further tension on the soft tissue structures in the forefoot, leading to rigidity (190). This unnecessary increase in pathological force on the foot can result in stiffness in the forefoot as a result of constant contraction of the intrinsic muscles and the deep fascia to stabilize the forefoot in response to the split second effect. In an MRI study of 40 subjects with MN and 29 subjects with other foot and ankle problems, Stecco *et al.* found the thickness of the dorsal fascia in the affected interspaces significantly greater in subjects with MN. They concluded that alterations in foot support and altered biomechanics act on the interosseous muscles, thus increasing the stiffness of the dorsal fascia and particularly at points where these muscles are inserted. It is important to note that the forefoot does get rigid in order to prepare for propulsion (60). However, chronic and excessive rigidity of this fascia increases the stiffness of the inter-metatarsal space, leading to entrapment of the common digital nerve. This stiffness and rigidity in the forefoot occurs over a period. The effect of ankle equinus may not be symptomatic initially and with advancing age the gastrocnemius gets tighter (191), leading to increased pathological forces in the forefoot.

One limitation of this study was that FPI is a static measurement and may not represent a subject’s dynamic function during gait, given that MN symptoms occur mostly during the propulsive phase of gait. However, some studies support the use of FPI as a valid tool in predicting dynamic function of the foot during gait (131, 192). Secondly, gender may have affected the results since 82% of the study subjects were female. However, no significant differences in mean ankle dorsiflexion measurements were noted between male and female subjects. Presentation of MN is more commonly seen

in women and in Australia their rate of hospital admission is three times higher than that of males (193).

This study examined the relationship of FPI, BMI and ankle dorsiflexion with MN. To our knowledge it is currently the only case-control study of this type in the literature. No significant associations were found between foot type or BMI and MN, nor between the FPI and interspaces affected by MN. However, a strong association was observed between the presence of MN and a restriction of ankle dorsiflexion. Future studies should investigate the effect of management of ankle equinus on MN treatment.

Chapter 5. Radiographic Analysis of Feet with and without Morton's Neuroma

Adapted from: **Naraghi R**, Bremner A, Slack-Smith L, & Bryant A (2017) Radiographic Analysis of Feet with and without Morton's Neuroma. *Foot & Ankle International* 38:310-317

5.0 Rationale of the Study

Most literature indicates the nerve involved in MN becomes enlarged and fibrosed as a result of repetitive trauma (20, 44, 63, 115). Injury to the nerve has been attributed to foot morphology (1), ankle equinus (12), and possibly to relative metatarsal lengths (10). Recently, metatarsal shortening osteotomies have been recommended to decompress MN (10, 18). Morton believed the symptoms associated with the condition were probably the result of having a short first metatarsal that caused an overload of the lesser metatarsals, thus traumatizing the common digital nerve (4). Patients with short and hypermobile first rays are observed to have higher plantar pressures beneath the second metatarsal, leading to transfer metatarsalgia (194, 195). Other factors are also discussed in the literature, such as the presence of hallux abducto valgus deformity and dorsiflexed first ray (145). These potentially increase the pressure under the lesser metatarsal heads and may also lead to MN formation.

One phenomenon that can be seen radiographically in the assessment of patients with MN is digital divergence. This can conceivably occur as a result of enlargement of the bursa-neuroma complex, which may place pressure at the base of the affected proximal phalanges (29, 86, 164). Digital divergence can also be seen in other pathologies such as digital contractures and plantar plate ruptures, which are normally ruled out as differential diagnoses when assessing MN. Grace *et al.* did not find any relationship between MN and digital divergence (29). However, their study did not include data on the size of the neuromas or on the interspaces that were affected by the divergences.

To our knowledge, there are no published studies that compare MN patients with control subjects in terms of the metatarsal parabola and radiographic measurement. The aim of this research was therefore to evaluate various structural measures in the forefoot of patients with MN. The radiographic measurements included lesser metatarsal length, first/second inter-metatarsal angle, hallux abducto valgus angle, first/second lateral inter-metatarsal angle and the effect of MN size as measured by ultrasound on digital divergence.

5.1 Methods

Weight-bearing dorsoplantar and lateral foot radiographs of subjects attending The University of Western Australia (UWA) Podiatry Clinic were used in this study. One hundred and one subjects (69 with MN diagnoses and 32 controls) were recruited to the study from 2011-2015, which was part of a larger research project investigating the aetiology of MN. This research project was approved by the Human Research Committee of UWA. All participants signed informed consent forms to use their radiographs for this study.

Inclusion criteria for MN subjects were a minimum of six-month history of neuroma symptoms, a clinically demonstrated painful Mulder's click, and ultrasound or MRI confirmation of MN. The inclusion criterion for control subjects was no history of MN or neuroma-like pain in the forefoot. Exclusion criteria for both neuroma and control groups were any previous history of surgery to the lower extremity, any proximal nerve entrapment at the level of the ankle, knee, hip or back, any history of significant trauma to the forefoot area (including plantar plate pathology), metatarsus adductus greater than 15°, any difficulty in walking or standing, diabetes or a history of systemic arthritis.

A single assessor performed the radiographic measurements for each patient using standard weightbearing dorsoplantar and lateral x-rays. The following angles were measured: lateral intermetatarsal angle (LIMA), inter-metatarsal angle (IM), hallux abductovalgus angle (HAV), digital divergence between the second and third digits

(DD23), digital divergence between the third and fourth digits (DD34) and relative metatarsal lengths of the first to fifth metatarsals (Met1-5). All radiographic measurements were performed via an IntelViewer System² computer program. Intra-tester reliability of all radiographic measurements was assessed on x-rays from five randomly selected subjects. These were reassessed one week after the initial measurements had been made and established the test-retest reliability of the radiographic measurements used in the study.

The LIMA was determined from the weightbearing lateral radiograph by placing a tangential line over the central portion of the dorsal cortex of the first and second metatarsal shafts. The angle between the two tangential lines was measured as described by Bryant *et al.* (Figure 5.1) (81). If the lines diverged distally the value was positive, while if the lines converged it was given a negative value.



Figure 5.1 Radiograph demonstrating Lateral intermetatarsal angle (LIMA)

The HAV angle was formed by bisecting the proximal phalanx and the first metatarsal, and measured as described by Gerbert (Figure 5.2) (196). The IM angle was formed by the bisection of the first and second metatarsal (Figure 5.2).

² <http://www.intelerad.com/en/products/inteleviewer/>



Figure 5.2 HAV and IM angles

The digital divergence angles (DD23 and DD34) were formed by bisecting the proximal phalanges of the second, third and fourth digits. The angles between these bisection lines were measured to assess the relative divergence of the digits on the affected interspaces (Figure 5.3).



Figure 5.3 DD23 and DD34 measurements

The relative metatarsal distances were measured using the Maestro technique (Figure 5.4) (78). The reliability of this measurement technique has been favourably reported in the literature (134). First, the M1 axis, defined as the ‘axis of the foot’, was drawn from the midpoint of the medial talar head to the distal lateral aspect of the calcaneocuboid joint. Next the SM1 line was drawn perpendicular to the M1 axis such that it bisects the fibular sesamoid. A line was then drawn parallel to the SM1 line and tangentially to the apex of the head of the second metatarsal. This was referred to as the SM2 line and its purpose was to measure the distance of all metatarsals relative to the second metatarsal. The relative length of each metatarsal is the measurement of the perpendicular line drawn from the apex of each metatarsal to the SM2. If the perpendicular line was above SM2 the value was assigned as negative, while if below a positive value was given.



Figure 5.4 Maestro technique to assess relative metatarsal lengths

The intra class correlation coefficient (ICC) for the LIMA, IM, DD23 and DD34 angles and the metatarsal distance measurements ranged between 0.95 and 0.99. Such values are generally considered to be excellent (197).

The size of MN was based on measurements from the transverse ultrasound image, as reported by radiology reports. Only participants with a transverse view measurement were included in this study.

Data were entered into Microsoft Excel and exported to IBM SPSS Statistics v23 for analyses. Independent Sample *t*-tests were used to compare the angle and distance measurements between the MN and control groups. Right and left feet were analysed separately to ensure data were independent. In addition, metatarsal length measurements of subjects with single neuromas were compared to those of control subjects. For these analyses, as well as distinguishing between right and left feet, the second and third interspaces were evaluated separately. Mann-Whitney U tests (MWU) were performed to take into account the reduced sample sizes and the non-normal

distributions of some of the measurements. Spearman rank correlation coefficients were used to assess relationships between neuroma size and digital divergence. Feet with both the 2/3 and 3/4 interspaces affected were not included since increased divergence in one interspace may affect the divergence in the adjacent interspace.

As insufficient data were available prior to this study to allow sample size calculations, retrospective power calculations were conducted using PS: Power and Sample Size Calculation (198). No mathematical correction was made for testing multiple associations. Instead, all results including 95% CIs and p-values <0.05 are reported.

5.2 Results

The study included 101 subjects, of whom 69 were diagnosed with MN and 32 were control subjects without MN. The mean $\pm$ SD age of MN subjects was 52 $\pm$ 15 years and for control subjects, 48 $\pm$ 12 years. The 69 MN subjects had 80 affected feet; the right foot was affected in 36 subjects and the left foot in 44 subjects. The number of interspaces affected for both right and left feet of MN subjects is shown in Table 5.1.

When comparing all feet, there were no significant differences in the LIMA, HAV, IM, digital divergence angles and the relative metatarsal distances between subjects with MN and control subjects (Table 5.2).

Table 5.1 The interspaces affected with MN for right, left and both feet

	2/3 interspace	3/4 interspace	Both interspaces	Total
Right foot only	13	12	0	25
Left foot only	12	13	8	33
Both feet	4	1	6	11
Total	29	26	14	69
Right foot total	17	13	6	36
Left foot total	16	14	14	44

Table 5.2 Comparison of radiographic measurements between MN and control groups by affected foot

	MN (L)	Control (L)	P-value	MN (R)	Control (R)	P-Value
	n=43	n=32	(95% CI)	n=37	n=32	(95% CI)
LIMA	0.29±3.03	-0.17±2.08	0.45 (-0.77,1.72)	0.64±1.93	0.07±2.26	0.26 (0.44,1.57)
HAV	13.38±7.18	11.3±7.18	0.28 (-1.78,5.94)	13.04±9.07	10.59±7.08	0.22 (-1.50,6.41)
IM	9.61±3.29	8.24±2.51	0.05 (-0.02,2.76)	8.61±3.06	8.02±2.78	0.40 (-0.82,2.00)
DD23	7.73±5.96	5.56±4.50	0.07 (-0.33,4.68)	6.97±5.06	5.07±4.67	0.11 (-0.45,4.26)
DD34	3.61±3.93	4.07±3.72	0.60 (-2.25,1.32)	3.03±3.72	4.36±3.98	0.15 (-3.18,0.52)
Met1	0.26±0.20	0.22±0.56	0.66 (-0.14,0.23)	0.24±0.35	0.28±0.32	0.59 (-0.20,0.11)
Met3	0.53±0.21	0.55±0.17	0.64 (-0.11,0.07)	0.52±0.21	0.49±0.17	0.49 (-0.06,0.13)
Met4	1.42±0.36	1.47±0.22	0.45 (-0.18,0.08)	1.40±0.38	1.34±0.25	0.45 (-0.09,0.21)
Met5	2.86±0.48	2.87±0.32	0.88 (-0.19,0.17)	2.85±0.49	2.72±0.28	0.16 (-0.05,0.33)

MN (Morton's neuroma), L (Left), R (Right), CI (Confidence interval), LIMA (Lateral intermetatarsal angle, degrees), HAV (Hallux Abducto valgus, degrees), IM (first and second intermetatarsal angle, degrees), DD23 (digital divergence between 2nd and 3rd toes, degrees), DD34 (digital divergence between 3rd and 4th toes, degrees), Met1 (relative first metatarsal length, cm), Met3 (relative third metatarsal length, cm), Met4 (relative fourth metatarsal length, cm), Met5 (relative fifth metatarsal length, cm), and P value reported by Independent Sample t-tests.

Second interspace measurement comparison

In the left foot, a significant difference in IM angles of MN subjects compared to control subjects was observed (mean 10.72 vs 8.24, respectively; MWU $p=0.02$, Table 5.3). In the right foot, a significant difference was found in the fifth metatarsal length of MN subjects compared to control subjects (mean 3.06 vs 2.72, respectively; MWU $p=0.01$). In the left foot the DD34 angles of the MN and control subjects differed significantly (mean 2.02 vs 4.07, respectively; MWU $p=0.02$) and similar differences were seen in the right foot (mean 0.86 vs 4.36, respectively; MWU $p<0.001$).

Third interspace measurement comparison

In the left foot, a significant difference in the Met4 of MN subjects compared to control subjects was observed (mean 1.29 vs 1.47, respectively; MWU $p=0.02$, Table 5.3). Similarly, in the right foot the Met3 and Met4 lengths of MN and control subjects differed significantly (mean 0.40 vs 0.49, respectively; MWU $p=0.03$, and mean 1.14 vs 1.34, respectively; MWU $p=0.02$, respectively).

The average MN size was 7.5 mm (range 3-12 mm) in transverse section as measured by ultrasound. No relationship between MN size and digital divergence was found in either foot, or in either neuroma location (Table 5.4).

Table 5.3 Comparison of radiographic measurements in subjects with MN in the second and third interspaces right and left foot

	2/3L	P-value MWU	2/3R	P-value	3/4L	P-value	3/4R	P-value
	n=16	(95% CI)	n=17	(95% CI)	n=14	(95% CI)	n=12	(95% CI)
LIMA	-0.28±4.26	0.24 (-1.94,1.72)	1.00±1.88	0.17 (-2.22,0.36)	0.27±1.63	0.30 (-0.82,1.71)	-0.11±2.26	0.59 (-1.31,1.69)
HAV	15.15±9.68	0.12 (-1.12,8.83)	15.03±8.45	0.09 (-9.01,0.13)	11.73±5.5	0.77 (-3.92,4.78)	12.41±10.20	0.90 (-7.30,3.65)
IM	10.72±3.52	0.02 (0.70,4.25)	8.72±2.41	0.42 (-2.31,0.90)	8.78±2.32	0.70(-1.05,2.12)	9.13±4.09	0.63 (-3.28,1.05)
DD23	8.95±7.15	0.05 (-0.67,7.46)	7.58±4.71	0.11 (-5.33,0.32)	4.94±4.59	0.62 (-3.54,2.30)	4.85±4.22	0.74 (-2.90,3.32)
DD34	2.02±2.69	0.02 (-4.1,0.05)	0.86±2.90	0.001 (1.29,5.70)	4.69±4.73	0.85 (-1.99,3.23)	6.40±2.97	0.07 (-4.60,0.51)
Met1	0.32±0.19	0.61 (-1.9,0.39)	0.13±0.33	0.10 (-0.41,0.35)	0.29±0.14	0.90 (-0.24,0.37)	0.34±0.25	0.57 (-0.26,0.15)
Met3	0.54±0.20	0.45 (-0.12,0.10)	0.59±0.19	0.10 (-0.20,0.01)	0.44±0.18	0.07 (-0.23,0)	0.40±0.18	0.03 (-0.02,0.21)
Met4	1.52±0.33	0.98 (-0.11,0.21)	1.54±0.31	0.05 (-0.36,-0.02)	1.29±0.34	0.02 (-0.35,0)	1.14±0.30	0.02 (0.02,0.38)
Met5	2.99±0.47	0.40 (-0.11,0.35)	3.06±0.41	0.01 (-0.53,-0.13)	2.73±0.45	0.17 (-0.38,0.08)	2.45±0.38	0.08 (0.05,0.47)

See Table 2 for control values.

2/3L (second interspace mean and standard deviation left foot), 2/3R (second interspace mean and standard deviation right foot), and 3/4L (Third interspace mean and standard deviation left foot), 3/4R (Third interspace mean and standard deviation right foot), and P value by MWU (Mann-Whitney U test).

Table 5.4 Correlation between MN size and digital divergence

Foot	Position	n	r	P-value
Right	2/3	13	0.370	0.21
	3/4	11	0.135	0.69
Left	2/3	12	0.184	0.57
	3/4	12	-0.047	0.88

5.3 Discussion

Metatarsal shortening osteotomy for ‘decompression’ of MN was introduced by Park *et al.* in 2013 (10). These workers retrospectively compared the outcomes for deep transverse metatarsal ligament (DTML) release in 46 MN patients with outcomes for 40 MN patients who underwent both DTML release and shortening of a lesser metatarsal utilising a Weil osteotomy. In their pre-operative evaluation of patients, metatarsal lengths were measured according to the technique described by Maestro *et al.* A Weil shortening osteotomy was performed on the longer metatarsal adjacent to the affected interspace. Outcomes were measured using the Foot Function Index and The American Foot and Ankle Society Forefoot Score. The outcomes for the group that received DTML release with Weil osteotomy were significantly better than those of the group that received DTML release only. However, there are no published case-control studies that evaluated the relative metatarsal lengths of patients with MN compared to a control group. The present study was therefore undertaken using radiographic measurements described by Maestro *et al.* in order to explore the validity of performing a surgically lesser metatarsal osteotomy for MN. No significant differences in the relative lengths of metatarsals were observed between the feet of MN and control subjects. However, some unusual findings were made for the single interspace comparisons with controls, although these may be due to chance in view of the relatively small sample size.

Menz *et al.* evaluated relative metatarsal lengths using the Maestro technique in older people with forefoot pain (n=40) and in a control group of older patients with no

forefoot complaint (n=70) (199). They found no association between pain in the forefoot and relative metatarsal lengths. However, using a MatScan^R system they found the peak plantar pressure under metatarsals 3-5 was significantly higher compared to the control group. They also observed a weak negative correlation between pressure in the forefoot and metatarsal length. Patients with forefoot pain were selected subjectively and none had a confirmed diagnosis of MN. The increase in pressure under the lesser metatarsals in this elderly group can perhaps be explained by fat pad atrophy and stiffness of the forefoot (200, 201).

Kaipel *et al.* (202) did not find any relationship between increased metatarsal length and plantar pressure in 91 patients with and without forefoot pain. They prospectively followed two groups of patients (51 feet in each group) with and without metatarsalgia, measured the relative metatarsal lengths using the Maestro technique, and performed plantar pressure measurements on an EMED-SF1 platform. These workers reported that relative metatarsal length had no effect on peak pressure or peak force. Their findings question the rationale of performing shortening osteotomies such as Weil osteotomy for the management of metatarsalgia.

Morton was the first to propose that hypermobility of the first ray resulting from a short first metatarsal and/or dorsal extension of the first metatarsal can result in lateral transfer of load to metatarsals 2-5 (4, 6). This phenomenon, known as “first ray insufficiency” (73) can lead to increased pressure in the lesser metatarsal area which Morton suggested could predispose to MN formation (74, 203). Breusch *et al.* reported MN development following Wilson osteotomy, which significantly shortens the first metatarsal (77). Bauer *et al.* also reported that short length of the first metatarsal is a risk factor for recurrence of MN after open neurectomies (18). However, using a technique first described by Hardy and Clapham, Grebing and Coughlin measured the relative difference in lengths of the first and second metatarsals for 46 control, 53 hallux valgus, 54 hallux rigidus, and 49 MN patients. They found no correlation between shortness of the first metatarsal and hypermobility of the first ray in all groups investigated (74). Similarly, the present study found no significant differences between

MN and control groups with regard to first metatarsal lengths, or relative lengths of the first and second metatarsals. Collectively, these findings question Morton's belief that short first metatarsals cause MN formation.

Measurement of the LIMA was used to evaluate the relationship between first ray elevatus and MN formation. We used the LIMA to determine whether the dorsal cortex of the first metatarsal was more elevated in relation to the second metatarsal on weight bearing lateral view of subjects. Even though the first metatarsal was more elevated in the MN group, the differences were not statistically significant. Roukis reported LIMA measurements of MN patients (n=50) and compared them to a group of patients with hallux rigidus, hallux valgus and plantar fasciitis (204). He found that LIMA in the hallux rigidus group was significantly greater than in other groups, including MN. Horton *et al* also measured first ray elevation using a different technique in three groups of patients with hallux rigidus (n=146), asymptomatic controls (n=50) and an MN group (n=64) (80). These authors reported no difference between the groups with respect to elevation of the first metatarsal head. Based on review of the literature and on the present findings, a significant relationship between MN and first ray elevatus cannot be demonstrated.

A limitation of measuring the LIMA is that the weight bearing lateral view depicts the foot during midstance (80). The pathological forces in MN are most likely caused during propulsion when maximum force is applied to the forefoot. During initial and final propulsion, strong forces are applied to the metatarsal heads (205). Future radiographic studies should investigate the change in first ray elevatus from midstance through propulsion in order to assess the role of the first ray in transferring load to the forefoot.

Lateral shifting of the hallux and increases in the IM angle have been described as possible causes of forefoot symptoms (77, 145, 199, 206, 207). Dietze *et al* performed a radio-kinematic and pedographic study in eight patients with HAV and first ray instability and found there was a significant increase in force transfer to metatarsals

2-4 (208). This transfer of force may cause overload to the forefoot and result in MN formation. Waldecker studied the plantar loading patterns in 50 patients with HAV and metatarsalgia and in 50 patients with HAV and no forefoot symptoms (145). He found a significant increase in peak pressure from medial to lateral across the forefoot in patients with HAV and forefoot pain. He explained this load transfer as a possible lack of the windlass mechanism which can occur as a result of increased hallux abduction and increased varus rotation of the first ray. In the current study the HAV and IM angles were compared between MN and control groups and no significant differences found.

To the author's knowledge, the only case control study on digital divergence was published in 1993 by Grace *et al* . These workers did not find a significant increase in digital divergence in MN subjects (n=48) compared to normal subjects (n=100). Their study did not state the size of the neuromas, nor did they report the divergence angles of the second and third interspaces separately. In the present study, no significant differences in the DD23 and DD34 angles were observed between MN and control groups. Based on the available data, no correlation was found between size of the MN and digital divergence.

One limitation of this study relates to statistical power. Retrospective calculations indicate the study had power of between 0.54 and 0.78 to detect differences of 2mm in metatarsal measurements, and a minimum power of 0.83 to detect a difference of 5 degrees in angle measurements when all MN and control subjects were compared. However, for the single interspace and digital divergence analyses, the sample size and hence statistical power was reduced. Another limitation of this study may be that females were approximately twice as frequent in the MN group. However, this represents the normal demographic presentation of MN as indicated by the three-fold higher rate of hospital admission for MN amongst females in Australia compared to males (193). Another potential limitation was the use of two dimensional weight-bearing dorsoplantar radiographs when examining metatarsal length. It would also be important to assess sagittal plane measurements of metatarsals when

investigating hyper-pressure of the forefoot as a possible aetiology for MN, as suggested by Bauer *et al.* (18). Future studies could conceivably measure coronal images of the transverse arch to assess the relative height of the metatarsals relative to the ground. As recommended by some statisticians,(209, 210) no statistical correction was made for multiple testing and instead all results were reported. Thus, some of the significant associations observed here could be due to chance.

In conclusion, this study did not find any relationship between metatarsal length and MN formation in symptomatic MN patients compared to a control group. Furthermore, no correlation was observed between the size of MN estimated using ultrasound images and radiographic evidence of digital divergence. Lastly, no significant relationship was seen between first ray elevatus or shortness of the first metatarsal and presence of MN, thus questioning the validity of Morton's early thoughts on the aetiology of MN.

Chapter 6. Plantar Pressure Measurements and Geometrical Analysis of Patients with and without Morton's Neuroma

The work presented in this chapter has been submitted for publication:

Naraghi R, Slack-Smith, L, Bryant A. *Foot & Ankle International* (submitted for publication, September, 2017)

6.0 Rationale of the Study

MN is a common cause of metatarsalgia affecting the second and third intermetatarsal spaces. It is more prevalent in females than males with the hospital admission rate for MN treatment being highest for females in the 50-55 years age category (193). Specific symptoms of MN include complaints of shooting pain, numbness and/or tingling in the second, third and fourth digits, burning sensation, cramping, and a feeling of “walking on a lump in the ball of the foot” (20). This is aggravated by walking in high-heeled shoes with a narrow toe box. MN is clinically diagnosed by Mulder’s click, which has 98% sensitivity for diagnosing this condition (88). MRI and ultrasound are equally effective in diagnosing MN (92), however a recent systematic review suggests that ultrasound may be more accurate than MRI with 90% sensitivity and 88% specificity (211).

Although there is debate over the exact aetiology of MN, the most common theories involve chronic trauma (2, 5, 18, 20, 115), abnormal metatarsal parabola (10), biomechanical factors such as pronation (5, 20) and or supination (8, 112) and equinus deformity (12, 172). These factors have been proposed to increase pressure in the forefoot and cause repeated trauma to plantar intermetatarsal nerves (50). An anatomical study by Kim *et al.* refuted the entrapment theory proposed by Gauthier (47) and postulated instead that MN was caused by pinching of the common digital nerve by the adjacent metatarsal heads and metatarsophalangeal joints during walking (50).

MN is a form of metatarsalgia and has been hypothesized to result from repeated loading of metatarsal heads (160). According to the aforementioned theories, increased pressure in the forefoot and under the metatarsal heads may traumatize the common nerve, thus leading to fibrosis and pathological changes.

MN is often managed conservatively with the use of metatarsal pads (212, 213). These are thought to lead to pain reduction by decreasing pressure on the nerve through widening of the forefoot (213). Recently Bauer *et al.* (18) and Catani *et al* (112) have advocated surgical treatment of MN using percutaneous metatarsal osteotomies to decompress the affected nerve. They proposed that symptoms of MN can be managed by addressing the ‘hyper-pressure’ of the affected metatarsal head. However, they did not evaluate plantar pressures before and after performing the metatarsal osteotomies in order to confirm a change in pressure. Surprisingly, no case-control studies have been reported in the literature that investigate the forefoot pressure of individuals with MN compared to an asymptomatic control group.

Other factors such as ‘wideness’ or ‘splay foot’ have been suggested as contributing to the aetiology of MN (15, 16, 163, 190, 214). The normal contour of the forefoot and the presence of the transverse arch across the metatarsals is an important mechanism by which shock absorption within the forefoot can occur during gait (16, 162, 215). Pathological conditions such as ‘splay foot’, ‘anterior flat foot’ or ‘collapsed metatarsal arch’ may increase the pressure in the forefoot and cause metatarsalgia (215). Additionally, ‘splay foot’ may also produce compressive forces in the forefoot when wearing shoes, leading to irritation of the affected nerve. Contrary to this, narrowness of the forefoot leading to closer proximity of the metatarsal heads and impingement of the nerve has also been suggested as a possible aetiology for MN (216). Park *et al.* did not find any significant differences in forefoot width, intermetatarsal angle and metatarsal distance between radiograph’s of MN subjects (n=84) and age and sex matched controls (n=84). However, their study was based on weightbearing radiographs that mimic midstance rather than during propulsion when the forefoot is dynamically under the greatest stress. Despite forefoot width often being cited as a

contributing cause of MN, there are no reports in the literature that have examined this factor dynamically.

Dynamic barefoot pressure data can be collected using the Emed-x® capacitance transducer matrix platform (Novel gmbh, Munich, Germany). This instrument has been shown to be a reliable tool for measuring plantar forefoot pressures and foot geometry (137, 142). The aim of this research was therefore to test the hypothesis that forefoot peak pressure, contact time and/or pressure time integrals are greater under the affected metatarsal heads of MN patients compared to control subjects. The second goal was to perform geometrical measurements such as forefoot width, foot length, coefficient of spreading, foot progression angle, and arch index. Finally, this study will investigate whether there is any correlation between increased forefoot peak pressures and forefoot width in subjects diagnosed with MN.

6.1 Methods

Approval was obtained from the University of Western Australia (UWA) Human Research Ethics Committee for this study (Approval RA/4/1/2543). Eighty-three participants consisting of 52 subjects with MN and 31 control subjects were recruited from the UWA Podiatry Clinic from 2012-2014. Controls consisted of 12 males and 19 females and the MN group consisted of 13 males and 39 females. Demographic information on the participants is provided in Table 6.1. The MN cases and controls were recruited by a University circular email advertisement. All subjects were given a patient information sheet and written consent was obtained to participate in the study. Inclusion criteria for MN subjects were a minimum six-month history of neuroma symptoms, a clinically demonstrated painful Mulder's click with ultrasound confirmation of MN. Ultrasound diagnosis of MN was made by an experienced musculoskeletal radiologist and assessed on both transverse and longitudinal axes as an abnormal ovoid hypoechoic thickening corresponding to the location of maximum tenderness (64). Each MN subject was clinically examined by a trained podiatrist as well as an experienced musculoskeletal radiologist to rule out any other source of pain

such as capsulitis and lesser metatarsal phalangeal joint instability such as plantar plate pathology. The inclusion criterion for control subjects was a negative history of MN or neuroma-like pain in the forefoot. Exclusion criteria for both the neuroma and control groups were any previous history of surgery to the lower extremity, any proximal nerve entrapment at the level of the ankle, knee, hip or back, any history of significant trauma to the forefoot area, rigid toe deformities, or an inability to ambulate without pain.

Table 6.1 Demographic description of Morton’s neuroma (MN) and control subjects

	Morton’s neuroma n=52	Control n=31
Age (years)	52±14	49±10
Weight (kg)	76±19	71±16
Height (meters)	1.67±0.07	1.64±0.10
Body Mass Index	27±6	26±4
Sex (Female/Male)	39/13	19/12
Feet studied	61	62
Foot (Right/Left)	30/31	31/31

6.1.1 Measurements

Dynamic peak plantar pressures, contact time, pressure time integrals and geometrical data were extracted using the Emed-x® platform (Novel GmbH, Munich, Germany) which was set flush to the floor within a 10-meter walkway. The Emed-x® platform is comprised of 6,080 capacitive sensors within a sensing area of 475 × 320 mm (sensor resolution of 4 sensors/cm²) and has a pressure range of 10–1270 kPa, accuracy of ±5%, and hysteresis <3% . The sampling frequency was 100 Hz. A two-step approach at a self-selected speed was utilized for all trials, which has been demonstrated previously to be as reliable as the mid-gait approach (139). Participants stood on the

platform and took two steps forward to determine the starting position. At the starting position, subjects were instructed to strike the platform on their second step. Subjects were instructed to use their usual gait while looking straight ahead and to avoid targeting the platform. Subjects practiced walking across the platform until he/she was comfortable with the procedure. Subjects performed five trials with the right and left feet, until a total of 10 successful steps were recorded. A trial was successful when only one foot contacted the platform, contact was made on the second step, and participants did not target the platform. Trials not meeting these criteria were excluded.

Emed-x® generated data were analysed using the Novel Database Medical Software Program (version 15.2.3, Novel GmbH). All measurements were calculated from the maximum pressure picture of the step during gait which corresponds to the contact or push-off phase of gait. The maximum pressure picture is a colour-coded image of the foot representing the maximum pressure value recorded by each sensor. The foot was divided into 10 regions (masks) using the Emed-x® Automask software. Masks for heel, midfoot, first to fifth metatarsal heads, hallux, second toe, and third to fifth toes (Figure 6.1) were used for analysis. For each mask the peak pressure (kPa) and contact times (msec) were measured. The pressure time integrals (kPamsec) under metatarsals 2-4 were measured to evaluate the cumulative effect of both pressure and time on MN formation. For each subject, the means of five measurements were used for statistical analyses. Five geometric measurements that included forefoot width (cm), foot length (cm), coefficient of spreading (forefoot width/foot length), foot progression angle (the angle between the axis of the foot and line of progression) and arch index (midfoot area divided by total foot area) were automatically calculated utilizing the software algorithms for each trial.

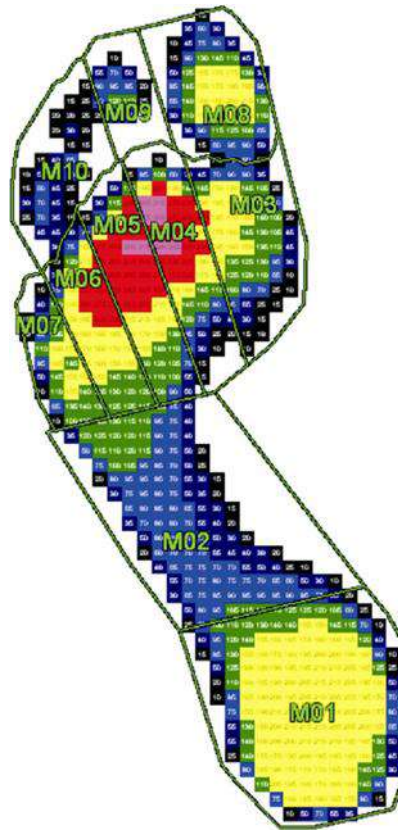


Figure 6.1 Ten mask areas depicted for peak pressure and pressure time integral measurements

6.1.2 Statistical analysis

All data were explored for normality prior to inferential analysis. Differences in peak pressure, contact time, pressure time integral and geometric data between participants with and without MN were determined using independent sample t-tests. Associations between coefficient of spreading and peak pressures during gait were determined using Pearson's r correlation coefficient. Cohen's recommendation for correlations was used, with 0.10 to 0.30 interpreted as a weak correlation, 0.30 to 0.50 as a moderate correlation, and greater than 0.50 as a strong correlation (217). All analyses were undertaken using SPSS Release 22.0 for Windows (SPSS, Inc., Chicago, IL), and p -values <0.05 were considered significant.

6.2 Results

No significant differences in age, weight, height and BMI were observed between the MN and control subjects (p value=0.28, 0.22, 0.22, and 0.31, respectively). The

number of affected interspaces with MN are summarized in Table 6.2. No significant differences were observed in the peak pressures of all masked areas and pressure-time-integrals under metatarsal 2-4 heads between MN and control subjects (Table 6.3). However, contact time on the right heel was reduced significantly in MN subjects compared to controls (Table 6.4). Contact times were not significantly different in all other masked areas. In addition, no significant differences were observed between the MN and control subjects in geometric measurements of forefoot length, width, coefficient of spreading, foot progression angle and arch index (Table 6.5).

Table 6.2 Interspaces affected in Morton's neuroma subjects

Interspace	Right Foot	Left Foot	Both Feet	Total
2/3	11	4	6	21 (40.4%)
3/4	8	10	1	19 (36.5%)
Both	2	8	2	12 (23.1%)
Total	21 (40.4%)	22 (42.3%)	9 (17.3%)	52 (100%)

Table 6.3 Mean $\pm$ SD of peak pressures for 10 masks and pressure time intervals for metatarsals 2-4

	MN R (n=30)	Control R (31)	P-value (CI)	MN L (31)	Control L	P-value (95%CI)
M1PP	342 $\pm$ 130	316 $\pm$ 73	0.25 (–80,21)	357 $\pm$ 111	327 $\pm$ 86	0.25 (–81,21)
M2PP	170 $\pm$ 58	156 $\pm$ 45	0.46 (–15,33)	148 $\pm$ 51	157 $\pm$ 43	0.46 (–15,33)
M3PP	298 $\pm$ 106	313 $\pm$ 127	0.32 (–113,38)	366 $\pm$ 151	328 $\pm$ 146	0.32 (–113,37)
M4PP	477 $\pm$ 174	494 $\pm$ 161	0.95 (–71,67)	476 $\pm$ 121	474 $\pm$ 150	0.95 (–71,67)
M5PP	461 $\pm$ 174	455 $\pm$ 151	0.96 (–59,62)	437 $\pm$ 117	439 $\pm$ 122	0.96 (–59,62)
M6PP	306 $\pm$ 99	297 $\pm$ 93	0.12 (–69,8)	303 $\pm$ 86	272 $\pm$ 65	0.12 (–69,9)
M7PP	227 $\pm$ 147	224 $\pm$ 124	0.87 (–61,52)	216 $\pm$ 125	211 $\pm$ 96	0.86 (–61,52)
M8PP	435 $\pm$ 213	454 $\pm$ 209	0.73 (–89,127)	446 $\pm$ 238	448 $\pm$ 195	0.96 (–108,113)
M9PP	206 $\pm$ 97	259 $\pm$ 360	0.44 (–83,189)	173 $\pm$ 124	199 $\pm$ 82	0.34 (–28,79)
M10PP	178 $\pm$ 69	151 $\pm$ 56	0.10 (–59,5)	116 $\pm$ 55	152 $\pm$ 85	0.05 (–0.37,72)
M4PTI	153 $\pm$ 65	154 $\pm$ 48	0.96 (–28,30)	154 $\pm$ 40	150 $\pm$ 48	0.72 (–27,19)
M5PTI	152 $\pm$ 69	146 $\pm$ 46	0.71 (–35,24)	148 $\pm$ 42	143 $\pm$ 42	0.65 (–26,17)
M6PTI	108 $\pm$ 36	106 $\pm$ 33	0.82 (–19,15)	109 $\pm$ 31	98 $\pm$ 26	0.1 (–26,3)

Peak Pressures (PP) measured in kilopascal (kpa) and and pressure-time -integrals (PTI) measured in kpams. Masked areas: M1 (heel), M2 (mid foot), M3 (first metatarsal), M4 (second metatarsal), M5 (third metatarsal), M6 (fourth metatarsal), M7 (fifth metatarsal), M8 (hallux), M9 (second toe), M10 (third, fourth and fifth toes).

Table 6.4 Mean± SD of contact time(msec) for 10 mask areas for MN and controls

	MN R (n=30)	Control R (31)	P-value (CI)	MN L (31)	Control L (31)	P-value (95% CI)
M1CT	424±68	462±71	0.04 (2,74)	445±96	451±79	0.79 (−39,50)
M2CT	490±85	524±89	0.13 (−10,79)	502±104	516±94	0.59 (−37,64)
M3CT	601±74	625±77	0.23 (−15,62)	632±78	610±97	0.35 (−66,23)
M4CT	633±72	655±73	0.24 (−15,59)	653±76	649±85	0.86 (−45,37)
M5CT	634±87	667±78	0.13 (−9,75)	664±74	665±86	0.96 (−40,42)
M6CT	639±74	658±76	0.31 (−19,58)	656±76	653±88	0.87 (−45,38)
M7CT	567±134	612±75	0.11 (−10,101)	603±78	605±88	0.92 (−40,44)
M8CT	517±113	570±109	0.07 (−3,110)	563±107	563±121	0.99 (−58,58)
M9CT	443±119	443±104	0.90 (−57,57)	426±126	476±97	0.08 (−7,107)
M10CT	535±111	507±116	0.34 (−86,30)	502±134	505±132	0.93 (−65,70)

CT contact time. See table 6.3 for definition of masked areas

.

Table 6.5 Geometric measurements (mean, SD and P-value) between MN and controls

	MN R (n=30)	Control R (n=31)	P-value (CI)	MN L (n=31)	Control R (n=31)	P-value (95% CI)
	Mean±SD	Mean±SD		Mean±SD	Mean±SD	
FL (cm)	25.83±1.54	25.5±1.71	0.49 (−1.12,0.55)	25.66±1.49	25.46±1.74	0.63 (−1.02,0.62)
FW(cm)	9.99±0.83	9.94±0.74	0.82 (−0.45,0.35)	10.12±0.76	10.00±0.76	0.53 (−0.51,0.26)
FPA (degrees)	9.85±5.83	10.71±5.89	0.56 (−2.13,3.87)	8.56±5.74	7.63±6.13	0.54 (−3.9,2.09)
COS	0.38±0.02	0.39±0.02	0.47 (−0.01,0.16)	0.39±0.02	0.39±0.02	0.67 (−0.01,0.01)
Arch Index	0.21±0.05	0.22±0.05	0.32 (−0.01,0.04)	0.20±0.06	0.22±0.05	0.11 (0.00,0.05)

FL Foot length, FW Foot width, FPA Foot progression angle, COS coefficient of spreading, MN Morton's neuroma.

A negative weak to moderate correlation (217) was observed between the coefficient of spreading on the right foot and third metatarsal head peak pressure ($r=-0.26$, $P=0.04$). On the left foot a weak correlation was observed between the coefficient of spreading and second metatarsal head pressure ($r=-0.28$, $P=0.03$). No significant correlations were observed between coefficients of spreading and all other metatarsal head pressures.

6.3 Discussion

The current study found no significant differences in peak pressure and contact time in 10 masked areas of the foot between patients affected with MN and controls. In addition, the pressure time integrals over the second through fourth metatarsal heads in subjects with neuromas were not significantly increased compared to the control group. This contrasts with the suggestion that peak pressure should increase in the forefoot in the immediate vicinity of a MN. Bauer *et al.* (18) believed that “hyper-pressure” under the metatarsals should be addressed for surgical management of MN. These authors performed a retrospective study comparing open neurectomy ($n=26$) and percutaneous deep transverse metatarsal ligament release with oblique osteotomy at the level of the head of the affected metatarsal on patients diagnosed with MN. They found the short-term clinical outcome for the percutaneous osteotomy group was as good as that of the open neurectomy group, with significantly better long term outcomes (18). A number of their subjects had other associated conditions such as hallux valgus, metatarsal phalangeal joint subluxation and toe deformities. MN can of course occur simultaneously in the presence of other forefoot conditions. However, it is also important to note that plantar pressure in the forefoot can increase in patients with digital deformities, hallux valgus, systemic arthropathies and neurological conditions (56, 136, 154, 156, 218). All the subjects in the present study had painful MN without any other forefoot problems, which may explain why “hyper-pressure” was not significantly different between the MN and control groups. In view of the results from this study, if lesser metatarsal osteotomies are being considered as treatment of MN it

would seem prudent to undertake preoperative plantar pressure measurements in order to confirm the need for osseous surgical intervention.

Previous studies investigating plantar pressure measurements of patients with generalised forefoot pain have demonstrated increased peak pressures in the forefoot (199, 202). Keijsers *et al.* however, attempted to classify forefoot pain based on plantar pressure measurements, but did not find any significant differences in peak pressures under the metatarsal heads between subjects with (n=283) or without forefoot pain (n=311) (219). None of the participants in their study had a confirmed diagnosis of MN and 207 subjects had other toe deformities, heel pain and ankle pain, which may have affected plantar forefoot pressures. In contrast to our findings, they found PTI and contact times under metatarsals two and three were significantly increased in the forefoot pain group in comparison to their asymptomatic group. They proposed that in subjects without foot deformities the peak plantar pressure under the heads of metatarsals was not as important as other factors such as plantar fat pad thickness and pain tolerance.

Our results showed no significant difference between the arch index of cases and controls which supports our previous findings using the Foot Posture Index (FPI) to compare foot type with the presence of MN (220). Although FPI is a static measurement of foot type, we did not see any difference in the arch index measured based on the dynamic plantar pressure measurement system. Therefore, based on our subjects, we can conclude that foot type may not be a sole predisposing factor in the pathogenesis of MN.

Logically, the presence of pain can potentially alter a person's gait pattern (221). At the time of the data collection all patients were pain free in order for them to meet the inclusion criteria and participate in the Emed testing. In this manner, it can be assumed that all MN subjects did not guard for pain with an unusual foot strike on the platform.

There was no significant difference between the width, length and coefficient of spreading between the MN subjects and controls. Based on previous studies males

have wider feet than females (215, 222). Male subjects constituted 39% of the controls and approximately 25% MN subjects. No attempt was made to separate males from females in either group for this part of the data analysis. This unequal distribution may have affected our results as there were higher percentages of males in the control group. However, recent study by Park *et al.* would seem to support our findings, and showed no significant differences between forefoot width and inter-metatarsal distances of patients with MN compared to a control group using weight-bearing radiographs (216). Their study did not show what happens to the width of the forefoot during push off phase. In our study we did not see any significant differences in forefoot width and coefficient of spreading dynamically between patients with and without MN.

Splayfoot has been associated with metatarsalgia by numerous authors (15, 16, 163, 215). It has been said that as the forefoot collapses in propulsion there is increase in pressure in the central metatarsals (15). We found no such correlation between the coefficient of spreading and peak pressure in the forefoot. To the contrary, a significant weak inverse relationship was observed between the coefficient of spreading and peak pressures under the second and third metatarsals of right and left foot. Duerinck *et al.* (205) studied forefoot deformation during forefoot loading in 40 normal subjects. They studied forefoot width and metatarsal height changes during all phases of gait cycle using a six-camera motion capture system and a RSscan pressure platform. Their findings suggested that the transverse arch height increased as the forefoot narrowed. This phenomenon can occur even though plantar pressure under the second and third metatarsals increase during propulsion despite elevated second and third metatarsal heights with forefoot narrowing. The increase in pressure may occur as a result of the windlass mechanism when the intrinsic and extrinsic muscles contract, which results in tightening of the plantar aponeurosis (35). This is in contrast to previous studies that concluded that the transverse arch collapses during propulsion (15, 161, 223). Our Emed results show higher peak pressures occur during the push off phase under second and third metatarsals compared to the first, fourth and fifth metatarsals. Therefore, based on our results and what has been described in the literature, as the foot

dynamically narrows, the pressure under the second and third metatarsal should increase during propulsion due to the forefoot becoming a much stiffer structure. This relative increase in stiffness of soft tissue and fascia surrounding the nerve has been implicated as a possible aetiological factor of MN (224). Perhaps a mechanism by which splay foot may lead to forefoot pain is that the windlass mechanism described above is prolonged leading to continued soft contracture which may injure the common digital nerve. Based on our selection criteria we had excluded any patients with other forefoot pain and deformities which may have included many subjects with splayfoot.

In conclusion, in our sample of MN and control subjects, we did not observe any significant increase in bare-foot peak pressure and contact time measurements. Similarly, there was no significant difference in width, length, foot progression angle, arch index, and coefficient of spreading between the two groups. Future studies should look at the plantar pressure and kinematic changes that occur from midstance to propulsion in relation to transverse arch changes that may occur in patients diagnosed with MN with a control group. The influence, if any, of different styles of footwear on forefoot measurements, including plantar pressures, in subjects with MN is another area of research that needs to be conducted.

Chapter 7. General Discussion and Conclusions

7.0 Introduction

This research was undertaken to gain a better understanding of the aetiology of MN, given the known gaps in the literature and possible impacts for clinical practice. An epidemiological study of MN was conducted using nation-wide hospital admissions data for Australia. Possible aetiologies for MN were also investigated using clinical studies based on previous literature implicating foot type, ankle equinus, BMI, relative metatarsal lengths, and plantar pressure measurements. This was the first study to investigate rates of hospital admissions for MN. Review of the literature also revealed a lack of case control studies that have investigated the association of foot type with MN, or associations between ankle equinus, metatarsal length and barefoot plantar pressure on MN formation. Similarly, the effect of BMI and geometrical parameters such as forefoot width and coefficient of spreading on MN formation have received only cursory investigation. This body of research was therefore aimed at addressing fundamental aspects of MN epidemiology and aetiology with the overall goal of assisting foot and ankle specialists to manage this condition. Currently, both conservative and surgical management is targeted at relieving symptoms rather than treating the cause of MN.

7.1 Hospital Admissions for Morton's Metatarsalgia in Australia (Chapter 3)

The specific aims of this study were to:

- (i) Describe MN admissions by patient sex and age group, using International Classification of Diseases, 10th Revision (ICD-10) diagnosis codes to

interpret total population data extracted from Australian Institute of Health and Welfare (AIHW)

- (ii) Measure the rate of admissions of MN in Australian hospitals
- (iii) Observe the ratio of female to male admissions.

7.1.1 Summary

Data were extracted for MN admissions to public and private hospitals across all Australian states and territories from the Australian Institute of Health and Welfare online database covering 1998 to 2008. The highest rate of admission for MN was found amongst women in the 50-54 year age group. For men, the highest admission rate was in the 55-59 year age group. Rates for every age group for the years 1998, 2001 and 2004 were determined. The highest rate in 1998 was in the 55-59 year age category at 22.10 per 100,000; in 2001 the highest rate was in 60-64 year olds at 23.60 per 100,000; and in 2004 the highest rate was in 55-59 year olds at 21.54 per 100,000. The rates for each of these three years varied slightly, however the female-to-male ratio remained constant at approximately 3 to 1.

7.1.2 Discussion

The findings for this epidemiological study are generally in agreement with the presentation of MN patients in daily practice. Most of the literature also reports that presentation of MN is more common in middle aged women (64, 91, 103, 115, 225).

This is the first study to use the AIHW data system to assess the rates of hospital admissions for MN across Australia. In addition, no study to date has reviewed large sample sizes for MN admissions that may reflect the general population of a particular country. Latinovic *et al.* (43) studied the rate of MN hospital admissions in England based on data collected from 253 general practices in 2006 (n=866). The present study investigated far more admissions (n=13,579) over a longer period (1998-2008).

Using Medicare scheduled item numbers from 1997 to 2006, a previous report showed that 11,037 neurectomies were performed in Australia by medical practitioners (170).

The highest incidence of neurectomies was observed in the 55-64 age group, which is also similar to the present findings.

7.1.3 Clinical Implications

Hospital admission information is important as it represents the more severe end of MN and could help to determine the need for services and provide an estimate of the cost of admissions. Knowledge of the affected age groups for hospital admissions could also help to inform preventive care of MN. Data provided by the AIHW can also help future studies of admissions for other foot and ankle pathologies.

7.1.4 Limitations

This study had the benefit of using total hospital admission data for Australia, however the quality of results is limited by the accuracy of this data, which was collected for administrative purposes and not validated for research. The study reflects the rate of hospital admissions (both public and private) for the surgical management of MN by podiatric and orthopedic surgeons. However, it did not capture patients diagnosed with MN in private or public clinics and hence does not reflect the true population incidence and is likely to underestimate total morbidity.

7.1.5 Recommendations for future studies

Future epidemiological studies should investigate other factors associated with hospital admissions, including comorbidities, health history and other demographic characteristics such as socioeconomic factors. MN has been associated with rheumatoid arthritis (70, 226) and other neuropathies such as that associated with diabetes (227). These and other predisposing factors may in turn lead to additional insights into the aetiology of MN.

7.1.6 Conclusions

The rate of hospital admission for MN is three times higher for women than men. For both sexes, the rate of admission for MN was highest in the 50-60 year age category.

This rate does not indicate the true prevalence of MN in Australia, but rather the rate of hospital admission for surgery, which in turn is likely to represent cases that are resistant to conservative treatment.

7.2 The Relationship between Foot Posture Index, Ankle Equinus, Body Mass Index and Morton's Neuroma (Chapter 4)

The aims of this study were to:

- (i) Investigate for possible associations between foot type (as measured by FPI), ankle equinus and BMI with the presence of MN
- (ii) Observe if a pronated and/or supinated foot predisposes to the formation MN, and investigate the inter-metatarsal spaces affected by MN.

7.2.1 Summary

This research compared the foot posture, body mass index (BMI) and ankle dorsiflexion of 68 subjects diagnosed with symptomatic MN with that of 32 asymptomatic control subjects. In addition, the effect of foot posture on the occurrence of MN in the second and third interspaces was investigated. The Foot Posture Index (FPI) was used to categorise foot posture, which has been demonstrated by previous investigators to be reliable. Ankle dorsiflexion was measured using the Silverskiöld technique, which is commonly used by podiatrists in clinical practice. In summary, no significant differences in FPI and BMI were observed relative to the MN interspaces affected, or between cases and controls. MN subjects had significantly lower ankle dorsiflexion measurements compared with control subjects.

7.2.2 Discussion

To our knowledge, this is the first case control study to investigate the effects of foot type, BMI and ankle flexibility on MN formation. No relationship was found between

foot posture and the occurrence of MN in a particular interspace. In the Framingham foot study published in 2013, MN was not associated with either a specific foot posture or function (173). Several authors have postulated that MN occurs more commonly in the third interspace of a pronated foot due to hypermobility of the lateral column relative to the medial column (5, 19, 63, 65, 228). However, this was not supported by the present findings. Based on the subjects studied here, MN does not appear to be associated with a particular foot type.

The second important finding was that patients with MN had significantly less available ankle dorsiflexion compared to the control group. Ankle equinus has been mentioned as a possible risk factor for MN (178, 229), however these opinions were not based on case-control studies of patients with or without MN.

7.2.3 Clinical implications

The present results indicate that foot type is not associated with the formation of MN. FPI is a valuable tool often used by podiatrists to assess the foot prior to orthotics therapy (132, 230, 231). This finding has clinical relevance as the use of functional foot orthosis for the management of MN is a common practice. Previously, Kilmartin and Wallace reported that pronation and supination orthoses were unsuccessful in relieving pain in 33 adult patients diagnosed with MN (68). However, since MN can occur concomitantly with other forefoot disorders, it is reasonable that clinicians prescribe functional foot orthotics to treat MN when there are signs and symptoms of mechanical overload of the forefoot.

Based on the number of subjects studied here, the ankle dorsiflexion measurements were significantly different between the MN and control subjects. Therefore, early treatment of ankle equinus could be useful in the management of MN. Currently there are no published calf stretching protocols relating to the treatment of MN.

7.2.4 Limitations

One limitation of this study was that FPI is a static measurement and may not represent a subject's dynamic function during gait, given that MN symptoms occur mostly during the propulsive phase of gait. However, some authors support the use of FPI as a valid tool in predicting dynamic function of the foot during gait (131, 192). Secondly, gender bias may have affected the results since 82% of participants were female. However, there were no significant differences in mean ankle dorsiflexion measurements between male and female subjects. Presentation with MN is more common in women and their rate of hospital admission in Australia is three times higher than that of males (193).

Another possible limitation of this study was the method by which ankle dorsiflexion was measured. The measurement technique used here has previously been reported in the literature as being unreliable (187, 188), although the intra-rater reliability in this study was found to be high (ICC of 0.95).

7.2.5 Recommendations for future studies

Future studies should aim to investigate the effect of management of ankle equinus on MN treatment. Amis, an orthopaedic surgeon in the USA, believes that calf stretching can help to alleviate the symptoms of MN (personal communication) (232). A recent systematic review by Young *et al.* maintained there was "some evidence to support the efficacy of stretching with or without the concurrent use of ultrasound, diathermy, diathermy and ice, heel raise exercises or warm up in increasing dorsiflexion range of motion at the ankle joint in healthy individuals" (233). In view of the present findings implicating an association between MN and reduced ankle dorsiflexion, the effect of stretching to potentially reduce MN symptoms should be explored.

7.2.6 Conclusion

No relationship was found between foot type or BMI and MN, nor was there any association between FPI and the interspace affected by MN. However, there was a strong association between the presence of MN and restriction of ankle dorsiflexion.

7.3 Radiographic Analysis of Feet with and without Morton's Neuroma (Chapter 5)

The aims of this study were to:

- (v) Assess the relative metatarsal length in subjects with and without MN to determine whether a relative increase in the length of lesser metatarsals and/or shortness of the first metatarsal is associated with MN
- (vi) Determine if patients with MN have an elevated first metatarsal compared to a group of asymptomatic subjects
- (vii) Investigate whether increased intermetatarsal and hallux abductus angles have an effect on MN formation
- (viii) Correlate the digital divergence angle measured on x-ray with the size of MN measured on ultrasound.

7.3.1 Summary

Numerous distance and angular measurements were made from weight-bearing radiographs of all symptomatic and control subjects. There were no significant differences in LIMA, HAV, IM, digital divergence angles or the relative metatarsal lengths between MN and control subjects. No significant associations were found between radiographic measurements and the interspace location of MN in symptomatic subjects. Furthermore, no associations were observed between increased divergence of the digits and increased diameter of MN.

7.3.2 Discussion

Morton was the first to suggest an association between a short first metatarsal segment and development of MN (75). A recent retrospective study of 100 asymptomatic individuals without MN and 84 patients with a confirmed diagnosis of MN reported the prevalence of a short first metatarsal to be 63% (234). However, the authors of this work did not provide details of the radiographic method they used to assess metatarsal length. Measurement of the first and second metatarsal lengths using the three most common methods (Coughlin, Maestro and Hardy and Clapham) has been reported to be quite variable (133). The Maestro technique used in the present study has been validated for high reliability and no significant differences in metatarsal length were found between symptomatic subjects and controls. Similar to the present finding, Grebing and Coughlin used the Hardy and Clapham technique and also found no correlation between shortness of the first metatarsal and hypermobility of the first ray in all groups investigated (74). Although it has been speculated that a short first metatarsal may be a causative factor in the development of primary metatarsalgia, the results of the present study suggest that MN is not related to a short first metatarsal segment, as initially suggested by Morton.

The relative lesser metatarsal lengths of MN subjects and controls were compared here in order to assess their importance in the formation of MN, as proposed by Park *et al.* (10). These authors suggested that nerve compression by the adjacent metatarsal heads was the primary aetiology of MN formation and recommended shortening the longer metatarsal of an affected interspace. Bauer *et al.* also hypothesized that “hyperpressure” of the metatarsal heads may be responsible for the pathogenesis of MN (18). At the time of performing the current research there were no published case-control studies that compared relative metatarsal lengths of subjects with and without MN. The present study used radiographic measurements as described by Maestro *et al.* in order to explore the rationale of performing lesser metatarsal osteotomies for MN. No significant differences in the relative lengths of lesser metatarsals between the feet of MN and control subjects were found. Based on these

findings, it is therefore difficult to justify performing lesser metatarsal shortening osteotomies as a routine procedure in the management of MN.

Similarly, no significant differences were observed between the MN and control groups for first ray elevation as measured on a weight-bearing lateral radiograph. Roukis reported LIMA measurements of MN patients (n=50) and compared them to patients with hallux rigidus, hallux valgus or plantar fasciitis (204). They found that LIMA in patients with hallux rigidus was significantly greater than in other groups, including MN. Horton *et al.* also measured first ray elevation using a different technique in subjects with hallux rigidus (n=146), asymptomatic controls (n=50) or MN (n=64) (80). They reported no differences between the groups with respect to elevation of the first metatarsal head. Based on review of the literature and the present findings, there appears to be no significant relationship between MN and first ray elevatus.

In addition, no correlation was found between digital divergence and increased size of MN as measured by ultrasound examination. Fourteen cases in two interspaces were excluded from this investigation and this may have affected the power of the study. The incidence of MN in adjacent interspaces has been reported to be high by Valero *et al.* in a study of 279 feet (235). These workers found that 97 (34.8%) of feet had single neuromas and 182 (65.2%) had multiple neuromas.

7.3.3 Clinical implications

Both Park *et al.* (10) and Bauer *et al.* (18) advocated metatarsal shortening osteotomies for the surgical management of MN. Based on the present findings and in the absence of any abnormal metatarsal parabola, we do not recommend metatarsal shortening osteotomy for the routine surgical management of MN. It is important that clinicians differentiate the main cause of pain in the forefoot by performing a thorough patient history, physical examination and relevant diagnostic tests prior to considering any surgical intervention. The MN subjects in this study had no other causes of forefoot pain and no significant differences were found in the radiographic measurements

between groups. However, subjects with symptomatic HAV deformities were not included in this study and hence it remains possible this deformity may still influence the development of MN.

7.3.4 Limitations

A limitation of measuring LIMA is that the weight bearing lateral view depicts the static foot that approximates midstance (80). The pathological forces in MN are most likely caused during propulsion when maximum force is applied to the forefoot. During initial and final propulsion, strong forces are applied to the metatarsal heads (205). Another limitation of the study was that the size of MN was estimated using ultrasound examination and hence may not be precise. Finally, for the single interspace and digital divergence analyses, the sample size and therefore statistical power was reduced because 20% of subjects had occurrences of MN in more than one interspace and were therefore excluded.

7.3.5 Recommendations for future studies

Future studies should ideally investigate a greater number of subjects for radiographic parameters in a single affected interspace. The radiographs reflect the foot during the mid-stance, but this may not provide an accurate representation of the position of the metatarsals during propulsion when the nerve is most likely being stretched or impinged. The possible impact of HAV deformity on the development of MN also requires careful investigation.

7.3.6 Conclusion

The current research failed to demonstrate any significant relationships between metatarsal length, IM, HAV and MN formation in symptomatic MN subjects compared to a control group. Therefore, based on these results and in the absence of an irregular lesser metatarsal parabola, it is difficult to justify metatarsal shortening for the routine surgical treatment of MN. Moreover, this research found no correlation between the size of MN measured using ultrasound images and radiographic evidence of digital

divergence. Lastly, no relationship was found between first ray elevatus or relative length of the first metatarsal and the presence of MN. This result does not support Morton's early thoughts on the aetiology of MN.

7.4 Plantar Pressure Measurements and Geometrical Analysis of Patients with and without Morton's Neuroma (Chapter 6)

The aims of this study were to:

- (i) Investigate peak pressure, pressure time integrals and contact time of patients with and without MN
- (ii) Investigate geometrical factors such as forefoot width, foot length, coefficient of spreading, and angle of gait with and without MN
- (iii) Determine if there is any correlation between an increase in peak pressure in the forefoot with increase in coefficient of spreading.

7.4.1 Summary

Dynamic peak plantar pressures, contact time, pressure time integrals, forefoot width, foot length, coefficient of spreading and arch index data were extracted using an Emed- x® platform on 61 subjects diagnosed with MN and on 31 control subjects. In addition, the association between coefficient of spreading of the forefoot and an increase in peak pressures in subjects with MN was investigated.

7.4.2 Discussion

There were no significant differences in peak pressure, contact time, and pressure-time integrals under the metatarsal heads of patients with or without MN. A previous study reported that increased length of the lesser metatarsals was not correlated with increased peak pressures under metatarsal heads in subjects with mechanical or primary metatarsalgia (202). Based on results obtained in bare-footed subjects, the

effects of peak pressure, pressure-time integral and contact time were not related to the presence of MN in the current study. In addition, this research did not find any significant associations between the presence of MN and foot length, forefoot width, coefficient of spreading, arch index or foot progression angle. With regard to forefoot width, these findings are similar to those of Park *et al.* who examined forefoot width and forefoot width:length ratios radiographically (216).

The present study found no significant difference between the arch index of cases and controls, thus supporting our earlier findings using the Foot Posture Index (FPI) to compare foot type with the presence of MN (Chapter 4 and (220)). Although FPI is a static measurement of foot type, no difference was observed in the arch index measure based on the dynamic plantar pressure measurement system. Based on this study, we therefore conclude that foot type may not be the sole predisposing factor in the pathogenesis of MN.

Splayfoot has been associated with metatarsalgia by numerous authors (15, 16, 163, 215). As the forefoot collapses in propulsion, the pressure in the central metatarsals is thought to increase (15). No such correlation was found here between the coefficient of spreading and peak pressure in the forefoot. To the contrary, a significant weak inverse relationship was observed between the coefficient of spreading and peak pressures under the second and third metatarsals of the right and left feet. Duerinck *et al.* (205) studied forefoot deformation during forefoot loading in 40 normal subjects. They studied forefoot width and metatarsal height changes during all phases of the gait cycle using a six-camera motion capture system and an RSscan pressure platform. Their findings suggest that transverse arch height increases as the forefoot narrows. This phenomenon can occur even though plantar pressure under the second and third metatarsals increases during propulsion, despite elevated second and third metatarsal heights with forefoot narrowing. The increased pressure may occur as a result of the windlass mechanism when the intrinsic and extrinsic muscles contract, resulting in tightening of the plantar aponeurosis (35). This contrasts with previous studies that concluded the transverse arch collapses during propulsion (15, 161, 223). The present

Emed results show that higher peak pressures occur during the push-off phase under the second and third metatarsals compared to the first, fourth and fifth metatarsals. Based on the present results and reports in the literature, we therefore conclude that as the foot dynamically narrows, the pressure under the second and third metatarsal increases during propulsion due to the forefoot becoming much stiffer. This relative increase in stiffness of the soft tissue and fascia surrounding the nerve has been implicated as a possible aetiological factor for MN (224). A possible mechanism by which splayfoot leads to forefoot pain is that the windlass mechanism is prolonged, thus leading to continued soft tissue contracture which may injure the common digital nerve. The selection criteria used in this study may have resulted in the exclusion of subjects with other forefoot pain and deformities that included some individuals with splayfoot.

7.4.3 Clinical implication

This study is the first to investigate plantar pressure parameters under lesser metatarsal heads in patient with MN and was performed to test the “hyper-pressure” theory proposed by Bauer *et al.* (18). Based on the findings, we again do not recommend percutaneous shortening and dorsiflexory osteotomies as surgical treatment for MN and as proposed by Bauer, in the absence of other problematic forefoot deformities. Similarly, these results question the validity of using insoles or orthoses designed to deflect pressure from the metatarsal heads of an affected interspace.

7.4.4 Limitations

A potential limitation of this study is that it was only possible to mask under the metatarsal heads of the forefoot to measure peak pressure, and not in the actual interspace between the metatarsal heads of the affected nerve. As plantar pressure measurement technology improves, it may become possible to isolate the small intermetatarsal spaces for measurement rather than the metatarsal heads. In addition, the effect of ankle equinus to increase in forefoot pressure was not assessed. Previous studies masked the whole forefoot to study the effect of ankle equinus (58, 59).

Orendurff *et al.* (59) found that despite a statistically significant relationship between decreased ankle flexibility and increased peak plantar forefoot pressures during walking, the relationship was weak ($R^2 = 0.149$). This suggests that other factors in addition to the indirect effect of ankle equinus, such as forefoot stiffness, may also play a role in increasing forefoot pressures.

7.4.5 Recommendations for future studies

Future studies should investigate in-shoe plantar pressure measurements using the Pedar® system or similar, to assess the effects of different footwear on plantar pressure in the forefoot. Shoe selection may be a major predisposing factor in the formation of MN and perhaps an important reason why MN is more common in the female population.

7.4.6 Conclusions

No significant differences between MN and control subjects were apparent in peak pressures of all masked areas and pressure-time-integrals under metatarsal 2-4 heads. Once again, based on the results of this study it is difficult to recommend shortening and/or dorsiflexory osteotomies for routine surgical management of MN.

No significant differences were observed between MN and control subjects for geometrical measurements of forefoot length, width, coefficient of spreading and arch index and increased pressure under the central metatarsals. This questions the notion that the transverse forefoot arch at the level of metatarsal heads collapses as a result of forefoot widening during propulsion.

7.5 Overall Synthesis

This research was conducted to further investigate the aetiology of Morton's neuroma as the literature was inconclusive. An epidemiological study was conducted to observe the trends of hospital admissions of MN patients in Australia. A series of clinical

studies were performed in order to test the commonly proposed aetiologies for MN. A pronated foot type (18, 25) and a cavus foot type (8) have both been implicated as possible aetiologies for MN. However, no study had yet investigated the possible effect of foot type using a reliable method such as FPI (130, 132, 236, 237) in subjects with and without MN. Moreover, even though ankle equinus has previously been implicated as a risk factor for MN (12, 14), no case-control studies had investigated this factor. The Silverskiold technique (14), used routinely in podiatric practice to assess the foot biomechanically prior to implementing orthotic therapy was used to measure for the presence of ankle equinus. In the subjects studies no association was found between foot type and MN. However, the presence of ankle equinus was a significant finding in MN subjects compared to controls and future studies should investigate the effect of the management of ankle equinus in the treatment of MN.

Abnormal metatarsal parabola has been implicated as a possible cause of MN (10). However, no significant differences in the relative lengths of all metatarsals were found in this study. Results for other factors such as first ray elevation as measured by LIMA and shortness of the first metatarsal found no association with the presence of MN, which agree with the findings of previous published studies (238) (74).

Peak plantar pressure and pressure-time intergral measurements were not significantly different between MN and control subjects in this study. This questions the hyperpressure theory for the pathogenesis of MN proposed by Bauer *et al.* (18). Based on the findings presented in this thesis, metatarsal shortening and/or dorsiflexory osteotomies cannot be recommended for the surgical management of MN in the absence of abnormal metatarsal parabola or other associated conditions of the forefoot.

This research suggests the aetiology of MN is likely to be multifactorial. We also believe that this is an acquired condition that may become symptomatic requiring admission to hospital for surgical excision. In the epidemiology study we found that the rate of admissions among men and women were highest in 50-60 age category and three times more common in women. The rate of admissions in the 60+ age category

declines, possibly because of decreasing mobility and increasing co-morbidity making them a less likely surgical candidate. In after 20-year age category we observed an increasing trend of hospital admissions in keeping with the acquired nature of the condition.

We believe it is likely that a combination of external factors such as occupation, plantar fat pad thickness, shoe gear and biomechanical influences such as ankle equinus may all have a role in the formation of MN. The fact that women had the highest rate of admissions implies that shoe gear is an important factor in the aetiology of MN. Indeed, the habitual wearing of high heel shoes can in itself induce an ankle equinus deformity that in turn may induce the formation of MN. The increased stiffness in the forefoot occurs as a result of direct forces produced by the “split second effect”, as explained recently by Amis (52). The thickening of fascia connected to the deep transverse metatarsal ligament proximally and overlying the intrinsic muscles of interossei and lumbricales may traumatize and entrap the common digital nerve when it passes through the intermetatarsal tunnel surrounded by deep fascia and adjacent metatarsals. The deep fascia overlying the intrinsics such as lumbricales further become stiff and thickened as a result of lesser metatarsal phalangeal joints continuously remaining in a hyper-extended position when in high heel shoes. The lumbrical muscle and tendon are in close proximity to the common digital nerve which may brush over the nerve leading to its traumatisation and entrapment.

Aging is also known to decrease the amount of fibro-adipose tissue, or the ‘fat pad’ of the foot (199). The physiological effects of aging (239, 240) that induce forefoot pathology (224) may also be important co-factors. Morton’s neuroma may well be associated with the presence of foot pathology that were excluded from this study. Anecdotally, it is common in clinical practice to see patients with MN present with other forefoot pathologies such as hallux valgus. However, the prevalence of MN and such structural forefoot deformities is not known and is deserving of further study.

A potential limitation of the research was the reliance on history, physical examination and ultrasound results to diagnose subjects with MN. Histopathology results could not be used to confirm the diagnosis of MN because most patients did not undergo surgery during the period of investigation. However, previous studies confirm that clinical and ultrasound examination provide an accurate means of diagnosing MN (84).

7.6 Conclusions

This research found that Australian hospital admissions for MN in the period studied occurred more commonly in women and in the 50-55 year age category.

The research did not find any relationship between the presence of MN and several measurable factors such as foot type, lesser metatarsal parabola, first metatarsal sagittal position or barefoot metatarsal dynamic pressures. However, the presence of ankle equinus was a significant finding between the MN and asymptomatic groups.

From a clinical viewpoint, this research suggests that metatarsal osteotomies are a questionable surgical technique for the treatment of MN in comparison to the more traditional approach of surgical excision. This research also raises the need to question ankle equinus management as a treatment for MN. Future studies should investigate the effect of calf stretching on symptomatic MN, as well as the influence of footgear as an aetiological factor for MN. This work also provides baseline data for undertaking future epidemiological studies, potentially strengthened by large sample clinical measures, as informed by this work.

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Appendix 1

Description of Total Population Hospital Admissions for Morton's Metatarsalgia in Australia

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Linda Slack-Smith, PhD†

Background: Morton's metatarsalgia is a painful perineural fibroma of a plantar nerve, most commonly of the second or third intermetatarsal spaces of the forefoot. The aim of this study was to investigate hospital admissions with a diagnosis of Morton's metatarsalgia in the Australian population from 1998 to 2008.

Methods: Data regarding admissions with a diagnosis code of ICD-10 G57.6 were extracted from the Australian Institute of Health and Welfare databases of hospital morbidity from 1998 to 2008. The event of interest was an admission with ICD-10 G57.6 (Morton's metatarsalgia). The explanatory variables included sex and age group. Rates were calculated using the estimated resident population counts to determine denominators.

Results: Morton's metatarsalgia admissions were almost three-fold higher for women in the population compared to men. The rate of admissions for Morton's metatarsalgia was the highest for the total population in the 55- to 59-year-old age group. Among women admitted for Morton's metatarsalgia, the highest rate was in the 50- to 54-year-old age group; among men, the highest rate was in the slightly older 55- to 59-year-old age category.

Conclusions: Population-level information on admissions for Morton's metatarsalgia show that admissions were three times higher among women compared to men. The highest admission rate was in the 50- to 55-year-old age group. (J Am Podiatr Med Assoc 104(5): 451-454, 2014)

Morton's metatarsalgia (also known as Morton's neuroma, interdigital neuritis, and neuralgia) is a painful condition in the plantar aspect of the forefoot attributed to the thickening and fibrosis of the common digital nerve at the level of the bifurcation into common digital branches.¹⁻⁷ Many sources report that this condition is more common in the second and third interspaces of the foot. Footwear seems to play a role in the formation of Morton's metatarsalgia in susceptible individuals,^{3,5} and the condition is said to affect mostly women who wear high-heeled shoes.⁴ The etiology of this condition is still unclear. The perineural tissue surrounding the nerve becomes enlarged and

thickened, possibly as a result of factors such as a trauma, compression from the deep transverse metatarsal ligament, metatarsus proximatus, and abnormal pressure.¹⁻⁵ The pain often radiates to the toes in the form of tingling and numbness, and most people describe the pain as "walking on a pebble." The literature indicates that it is more common in women, but men are also affected by this malady.^{1-3,7} The condition is treated conservatively by changing shoe gear, and by using metatarsal padding, orthosis, cortisone, or alcohol injections. Failure to respond to conservative care may necessitate surgical excision of the affected nerve.

There is a dearth of epidemiological data regarding hospital admissions for Morton's metatarsalgia internationally. The purpose of this article is to describe the epidemiology of hospital admissions for Morton's metatarsalgia in Australia, including the description of admissions by patient sex and age group, using International Classification of Diseases, 10th Revision (ICD-10) diagnosis codes.

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Methods

We extracted data on Morton's metatarsalgia admission to public and private hospitals across all Australian states and territories from the Australian Institute of Health and Welfare online database from 1998 to 2008.⁸ Individual-level data were not available. The data have been recorded based on standardized International Statistical Classification of Diseases and Related Health Problems, 10th Revision, Australian Modification (ICD-10).⁹ The ICD-10 code of G57.6 corresponds to Morton's metatarsalgia. The factors extracted from the online data were total number of admissions, age, sex, and age groups of patients admitted with an ICD-10 code of G57.6. The male-to-female ratio and percentage of admissions within each age group were determined.

The ICD-10 code G57.6 was used to allow the investigators to look at admissions for this disorder using the Australian Institute of Health and Welfare (AIHW) data.⁸ The AIHW is an Australian Government organization that provides information and statistics on Australian health and welfare matters.

Estimated resident population counts of all sociodemographic stratifications for 1998 to 2008 were available from the Australian Bureau of Statistics.¹⁰ Rates were generated by dividing the number of hospital admissions of Morton's metatarsalgia by the estimated resident population of the same specified group and multiplying by 100,000 to determine the number of hospital admissions per 100,000 people per year. The rates for 3 years (1998, 2001, and 2004) were calculated to observe the variation over time. The standard error formula for rates was used to derive standard errors and consequent 95% confidence intervals. Findings were considered significant at the $P < 0.05$ level.¹¹ We used publicly available raw data and received approval for this project from the Human Research Ethics Committee of the University of Western Australia.

Results

There were 13,579 hospital admissions with a diagnosis of Morton's metatarsalgia from 1998 to 2008 (Table 1); 3,266 patients were male and 10,313 were female. The average female-to-male ratio was 3.2 to 1.0. The highest rates of admission for Morton's metatarsalgia among women were in the 50- to 54-year-old age group; for men, the highest admission rates were in the 55- to 59-year-old age group (Fig. 1). The highest rate for women was in

2001 at 10.92 and for men in 1998 at 4.01 per 100,000 populations per year (Table 2). Over the period reviewed, the highest overall rate for the total population study from 1998 to 2008 occurred in 1998 at 7.43 per 100,000 population. The rates for every age group for the years 1998, 2001, and 2004 were determined (Table 1). The highest rate in 1998 was in the 55- to 59-year-old age category at 22.10 per 100,000; in 2001, the highest rate was in the 60- to 64-year-old category at 23.60 per 100,000; and in 2004, the highest rate was in the 55- to 59-year-old age category at 21.54 per 100,000. The rates for each of these 3 years varied slightly; however, the female-to-male ratio remained constant at approximately 3 to 1.

Discussion

Although a number of studies have investigated the outcome of surgery on patients with Morton's metatarsalgia, previous studies have not used population data. Bradley et al¹² found from 85 individuals who underwent Morton's neuroma surgery, there were 71 females and 14 males (ratio of 5 to 1). In a 1979 study, Gauthier¹³ sectioned the deep transverse intermetatarsal ligament of 206 individuals, 187 females and 19 males, with a ratio of approximately 10 to 1. Other ratios of female to male who have had surgery for Morton's metatarsalgia have been reported in the literature¹²⁻¹⁴; however, no study to date has reviewed large sample sizes that may reflect the whole general population of a particular country.

In 2006, Latinovis et al¹⁵ studied data on the incidence of common compressive neuropathies from 253 general medical practices across the United Kingdom. Morton's metatarsalgia was found to be more common in women, and in both men and women between 55 and 64 years of age, which is similar to our findings; the male-to-female ratio was 1.8 to 1.0. They also studied the rate of the operative treatment and found a 2.3 to 1.0 female-to-male ratio, which is also very close to our results. Their study, however, was based on number of general practitioner practices across the United Kingdom and does not necessarily resemble the total population.

Limitations of the Study

Although our study has the benefit of using total population data for Australia, the use of administrative data is a limitation in that the quality of the results depends on the accuracy of the data. This

Table 1. Age Group, Total Number of Admissions, Percent of Admissions, and the Rates per Year per 100,000 Populations for the Years 1998, 2001, and 2004

Age Group	Total No. Admissions (1998–2008)	Total % Admissions	Rate 1998	Rate 2001	Rate 2004	Mean Rate	95% CI
1–19	62	0.45	1.41	0	0.22	0.54	0–2.03
20–24	157	1.16	2.34	1.46	0.57	1.46	0–3.19
25–29	345	2.54	3.69	2.84	1.99	2.84	1.17–4.50
30–34	603	4.44	4.39	6.34	3.41	4.71	1.79–7.64
35–39	1,031	7.59	7.81	8.11	6.01	7.31	5.08–9.53
40–44	1,204	8.87	9.02	8.31	6.35	7.89	5.18–10.61
45–49	1,660	12.22	12.68	13.32	11.97	12.66	11.33–13.99
50–54	2,267	16.69	20.01	18.53	14.90	17.81	12.67–22.96
55–59	2,258	16.63	22.10	19.53	21.54	21.05	18.41–23.70
60–64	1,743	12.84	19.48	23.60	19.70	20.93	16.38–25.47
65–69	1,075	7.92	17.68	12.75	17.18	15.87	10.55–21.19
70–74	672	4.95	12.75	9.24	9.90	10.63	6.97–14.29
75–79	338	2.49	6.60	8.86	6.98	7.48	5.11–9.85
80–84	140	2.49	4.10	4.85	4.44	4.46	3.73–5.20
85+	24	1.03	0.44	0.75	1.38	0.86	0.09–1.63
Male	3,266	0.18					
Female	10,313	24.05					
Total	13,579	75.95					

study reflects the rate of admission of only patients diagnosed with Morton's metatarsalgia across Australia, who were admitted to public and private hospitals presumably for surgical management of the condition by both podiatric and orthopedic surgeons. It does not represent all patients diagnosed with Morton's metatarsalgia in private or public clinics and hence does not represent the true

incidence in the population and is likely to be an underestimate of total morbidity. However, the hospital admission information is important to determine the need for services and estimating the cost of admissions relating to Morton's metatarsalgia.

Another limitation is the variation in definition of the code G57.6. The ICD-10 defines G57.6 as

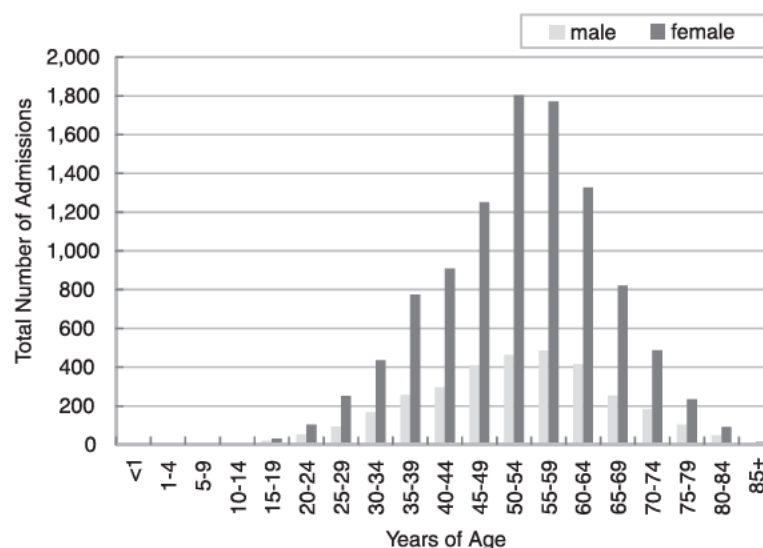


Figure 1. Number of admissions for Morton's metatarsalgia among men and women by age group in years.

Table 2. Rates for 1998 to 2008 Male and Female (Admissions per 100,000 per Year)

Years ^a	1998– 1999	1999– 2000	2000– 2001	2001– 2002	2002– 2003	2003– 2004	2004– 2005	2005– 2006	2006– 2007	2007– 2008
Rates, male	4.01	3.32	3.4	3.63	3.37	3.01	2.93	2.84	3.46	3.24
Rates, female	10.81	10.06	10.46	10.92	9.90	9.64	10.65	10.13	10.38	10.47
Total	7.43	6.71	6.89	7.30	6.66	6.36	6.82	6.51	6.94	6.88

^aYears represent Australian financial years July 1 to June 30.

Morton's metatarsalgia while the Australian Institute of Health and Welfare defines G57.6 as the lesion of the plantar nerve.⁸ Another limitation is that we assume most people will have only one admission and that they are not readmitted for recurrent Morton's metatarsalgia or any other complications relating to this pathology. In our experience, the most common plantar nerve lesion or pathology is Morton's metatarsalgia (a.k.a. Morton's neuroma, and interdigital neuralgia).

Conclusions

This article has provided analysis of total population data for Morton's metatarsalgia in Australia using the Australian Institute of Health and Welfare databases of hospital morbidity from 1998 to 2008. Such data are useful for morbidity and cost estimates. Although somewhat complex to access and manage, these data are publically available and can be used to follow the trends for this disorder. From the results, we see that the rate of Morton's metatarsalgia admission is three times more common in women and has the highest admission rate in the 50- to 55-year old category at 10.9 per 100,000 of population.

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Appendix 2

RESEARCH

Open Access



The relationship between foot posture index, ankle equinus, body mass index and intermetatarsal neuroma

Reza Naraghi^{1*}, Alexandra Bremner², Linda Slack Smith³ and Alan Bryant¹

Abstract

Background: The main purpose of this study was to investigate the presence of an association between intermetatarsal neuroma and foot type, as measured by the Foot Posture Index. The study also examined whether there was a relationship between foot type and the interspace affected with intermetatarsal neuroma, and whether ankle equinus or body mass index had an effect.

Methods: In total, 100 participants were recruited from The University of Western Australia's Podiatry Clinic, 68 of whom were diagnosed with inter metatarsal neuroma from 2009 to 2015. There were 32 control participants recruited from 2014 to 2015. The age of subjects was recorded, as were weight and height, which were used to calculate body mass index. The foot posture index and ankle dorsiflexion were measured using standard technique. Independent t tests and Kruskal Wallis tests were used to compare differences in foot posture index, body mass index and ankle dorsiflexion between the inter metatarsal neuroma and control groups. Multivariable logistic regression was also used to model relationships for outcome.

Results: The 68 intermetatarsal neuroma subjects had a mean age of 52 years (range 20 to 74 years) and comprised of 56 females and 12 males. The 32 control subjects had a mean age of 49 years (range 24 to 67 years) with 26 females and six males. There were no significant differences between the control and the intermetatarsal neuroma groups with respect to the mean foot posture index scores of the left and right foot ($p = 0.21$ and 0.87 , respectively). Additionally no significant differences were detected between the affected intermetatarsal neuroma interspace and foot posture index ($p = 0.27$ and 0.47 , respectively). There was no significant difference in mean body mass index between the intermetatarsal neuroma (26.9 ± 5.7) and control groups (26.5 ± 4.1) ($p = 0.72$). There was, however, a significant difference in mean ankle dorsiflexion between the intermetatarsal neuroma and control groups ($p < 0.001$ for both feet). Logistic regression models, adjusted for age, sex, foot posture index and body mass index estimated that the odds of having an intermetatarsal neuroma in the right foot increased by 61% (OR 1.61; 95% CI 1.32–1.96) with each one degree reduction of ankle dorsiflexion, and in the left foot by 43% (OR 1.43; 95% CI 1.22–1.69).

Conclusion: No relationships were found between foot posture index and body mass index with intermetatarsal neuroma, or between foot posture index and the interspaces affected. However, a strong association was demonstrated between the presence of intermetatarsal neuroma and a restriction of ankle dorsiflexion.

Keywords: Neuroma, Equinus deformity, Body mass index

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Background

Intermetatarsal neuroma (IMN), also known as Morton's metatarsalgia is the symptomatic thickening of the plantar intermetatarsal nerve at the level of bifurcation into the digital branches. It is more common in women, and the highest hospital admission rates for surgical removal are for 55–59 year-old males and 50–55 year-old females [1]. People with IMN complain of a sharp burning pain in the interspaces and tingling sensations that may radiate to the toes. This condition commonly affects the third interspace, however, neuromas in the second interspace are also common, while the first and fourth interspaces are rarely involved [2–6].

There are numerous aetiologies speculated in the literature for IMN, such as; pronation [4, 7, 8], metatarsus proximatus [15, 16], trauma [9], ankle equinus [10–14], bursitis [9, 15, 16], entrapment by the deep transverse metatarsal ligament [9, 17], and anatomical variations such as presence of the communicating branch of the lateral plantar nerve [7, 18, 19]. Jarde reported that flatfoot was associated with the development of IMN in 44% of a 43 patient series [20]. Hagedorn et al., in a 2013 study of 3429 participants, reported associations between foot posture and common foot problems such as hallux abducto valgus, hammertoe, overlapping toe, hallux rigidus and IMN [21]. Their results showed no association between IMN ($N = 439$) and any foot posture and function. However, their study did not compare the foot posture of subjects with foot disorders to that of control subjects.

Excessive pronation can lead to hypermobility of the metatarsal heads, and it has been postulated that movement between the fixed medial column and the more mobile lateral column of the foot can place excessive pressure on the third interspace nerve [4, 7, 15, 20, 22, 23]. This, along with the traction caused by the flexor digitorum brevis has been implicated as a possible cause of the formation of neuroma in the third interspace [4]. It has been suggested that neuroma in the second interspace is more common in the neutral to cavus foot due to the close approximation of the second and third metatarsal heads [24]. This tight space predisposes the nerve to compression by the bursa above the nerve and lumbricalis muscle/tendon arising from the medial aspect of the flexor digitorum longus that runs parallel to the nerve [25, 26]. Furthermore, the plantar declination of the metatarsals in a cavus foot type can increase pressure over the corresponding nerve [27]. Pazzaglia et al. reported that 75% of his IMN patients ($n = 12$) in an immunohistochemical study had a cavus foot type with forefoot deformity [6]. There were no case-control studies in the literature that investigated the association of IMN with foot posture. Additionally no proposed mechanism that related foot posture to the occurrence of IMN in the second and third interspaces was

identified. This lends us to hypothesize that the occurrence of neuroma in the third interspace would be associated with a pronated foot posture and the occurrence of neuroma in the second interspace would be present in a more neutral to supinated foot type.

To measure the association of foot posture and IMN, investigators can use a simple and efficient tool such as The Foot Posture Index™ (FPI). FPI is regularly used by clinicians to assess foot type prior to implementing orthotic therapy [28]. The FPI measurement tool has also been validated using Rasch analysis, “which showed that it had good psychometric properties, good individual item fit, and good overall fit of the six criteria to the obtained model” [29]. In addition, Cornwall et al. showed that the FPI had high intra-rater reliability with intraclass correlation coefficient (ICC) levels of greater than 0.9, however, the inter-rater reliability with ICC values were moderate between 0.525 and 0.655 [30]. Although there is no available literature that has investigated the FPI and IMN, this tool is frequently reported for association of foot type with many other lower extremity conditions [31–33].

Reduced ankle joint dorsiflexion also known as ankle equinus is surmised to cause IMN [10, 13, 14, 34, 35]. A lack of adequate ankle dorsiflexion can result in compensation during gait such as; an early heel lift and an increase in forefoot pressures [11] and thus causing pain in the forefoot [14]. Measurement of ankle joint dorsiflexion is used frequently by clinicians in their day to day practice. There is limited high quality evidence to support the relationship between ankle joint range of motion and IMN, only one case study by Barrett and Jarvis reported an improvement to forefoot nerve symptoms after a gastrocnemius release [35].

This study investigates the association between foot type as measured by the FPI, ankle equinus and body mass index (BMI) and the presence of IMN. This study examines the relationship between foot type and the affected interspace with neuroma.

Methods

As a case-control study, subjects were recruited from patients attending The University of Western Australia (UWA) Podiatry Clinic. The inclusion criteria for IMN subjects included a minimum of 6-month history of pain in an affected interspace and a clinically demonstrated positive painful Mulder's click and a positive ultrasound confirmatory diagnosis of neuroma in the affected interspace. The inclusion criterion for control subjects was no history of IMN or neuroma-like pain in the forefoot. The exclusion criteria for both neuroma and control groups were a previous history of surgery to the lower extremity, any proximal nerve entrapment at the level of the ankle, knee, hip or back, any history of significant

trauma to the forefoot area, any difficulty in walking and standing, diabetes or a history of systemic arthritis, bony ankle equinus and any other cause of pain in the forefoot such as capsulitis/tenosynovitis or plantar plate pathology.

Recruitment

Approval was obtained from the University of Western Australia Human Research Ethics Committee for this study, which recruited 100 participants from the UWA Podiatry Clinic, 68 of whom were diagnosed with IMN from 2009 to 2015. There were 32 control participants recruited from 2014 to 2015. All participants provided a medical history and underwent a physical examination by the corresponding author.

Measurements

Subjects' ages, weights and heights were recorded, and their BMIs calculated. The FPI was measured according to the FPI User Guide Manual [36] by the corresponding author, who has more than 10 years of experience in clinical practice. Measurements were taken twice and the average value was recorded. Ankle dorsiflexion was measured for each subject with a goniometer using the technique described by Root et al. [37]. The subtalar joint was placed in neutral with the patient in a prone position and the ankle dorsiflexed passively while maintaining subtalar joint neutral position. The subject was then asked to actively dorsiflex the foot while the examiner maintained the subtalar joint in a neutral position. The angle formed between the lateral rear foot and the lateral bisection of the distal 1/3 of the fibula was measured. Two measurements were taken and the average recorded. The intra-rater reliability of the ankle dorsiflexion measurements was tested by using the measurements of eight subjects performed three times to calculate the ICC using a two-way mixed effects model in IBM SPSS Statistics v22 (IBM Corp, Armonk, NY, USA). The ICC of 0.95 (95% CI 0.83–0.99) indicated that intra-rater reliability was good.

Statistical analysis

IBM SPSS Statistics v22 was used for analyses. The significance level was set at 0.05. Results are expressed as mean $\pm$ SD. Medians and ranges are also presented for non-normally distributed measures. Independent sample *t*-tests were used to compare the mean age, BMI, FPI and ankle dorsiflexion between IMN and control groups. In addition, Kruskal-Wallis tests were performed to test for differences in foot type and ankle dorsiflexion between the interspaces affected. Chi-square tests were used to determine whether there was any association between the interspace(s) and the foot (feet) affected in IMN subjects, and whether the proportions of males and females with ankle dorsiflexion of less than 10° differed.

Associations were also investigated using multivariable logistic regression. Odds ratios (ORs) and 95% confidence intervals (CIs) are reported.

Results

The 68 IMN cases had a mean age of 52 ± 14 years (range 20 to 74 years) and comprised 56 females and 12 males. The control group of 32 subjects had a mean age of 49 ± 10 years (range 24 to 67 years), with 26 females and six males. There were no significant differences in age between the IMN and control groups ($p = 0.28$), or BMI between the IMN (26.9 ± 5.7) and control (26.5 ± 4.1) groups ($p = 0.72$). Approximately equal percentages of men and women had IMN: 66.7% of men and 68.3% of women ($p = 0.89$).

Figure 1 shows the FPI scores for the IMN and control groups. The mean FPI scores were 3.5 ± 2.9 (range -5 to 8) for the right-foot IMN and 2.9 ± 2.8 (range -1 to 7) for the left-foot IMN (Table 1). The control group mean FPI score for the right foot was 2.7 ± 2.5 (range -3 to 7) and for the left foot, 3.0 ± 2.9 (range -5 to 8). There were no significant differences in the mean FPI scores for the right and left feet between cases and controls ($p = 0.21$ and 0.87, respectively). There were, however, significant differences in mean ankle dorsiflexion between the IMN and control groups ($P < 0.001$ for both feet). The ankle dorsiflexion measurements of IMN subjects were lower by 5.91° (95% CI 4.04–7.78) for the right foot, and 7.34° (95% CI 5.55–9.13) for the left foot. Figure 2 shows the ankle dorsiflexion measurements of the IMN and control groups. Male and female ankle dorsiflexion measurements did not differ significantly, nor did the proportions of male and female IMN subjects with ankle dorsiflexion less than 10 degrees. They were 87.5% versus 75.0% on the right ($p = 0.66$), and 75.0% versus 86.7% on the left ($p = 0.59$), for males and females, respectively.

Of the IMN subjects, 28 were diagnosed with neuroma in the second interspace, 23 in the third interspace and 17 in both 2nd and 3rd interspaces. Only three subjects had neuromas in the second and third interspaces of both feet (Table 2). There was no significant association between the interspace(s) affected and the foot (feet) affected with IMN(s) ($p = 0.16$).

In order to evaluate the relationship between FPI and interspaces affected the IMN subjects were divided according to their affected interspace and compared with controls. The second interspace FPI means on the right ($n = 19$) and left ($n = 13$) were 3.2 ± 2.6 and 2.7 ± 1.9 , respectively. The third interspace FPI means on the right ($n = 15$) and left ($n = 11$) were 3.20 ± 3.5 and 2.9 ± 2.8 , respectively (Table 3). FPI did not differ significantly across groups when IMN subjects were divided according to their affected interspace(s) ($p = 0.27$ on the right and $p = 0.47$ on the left) nor did ankle dorsiflexion

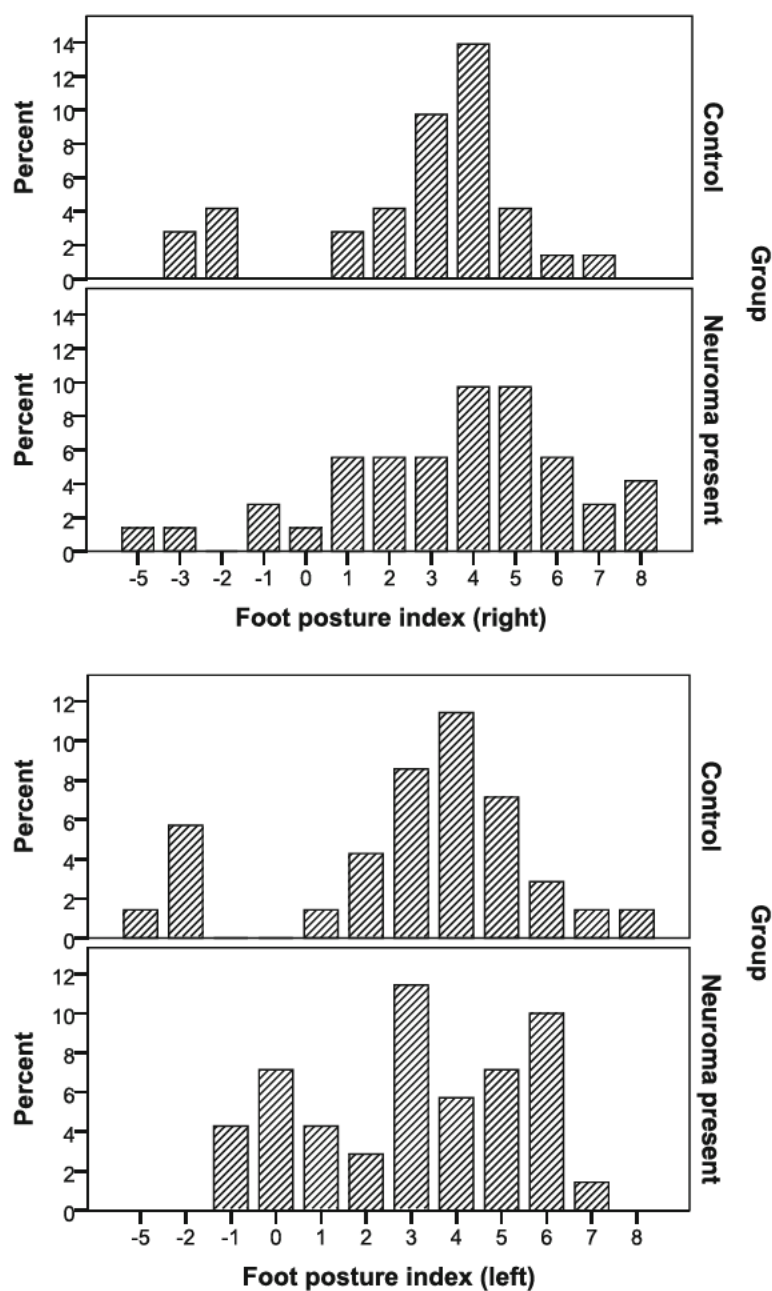


Fig. 1 Graph of foot posture index for intermetatarsal neuroma and control groups left and right feet

Table 1 Comparison of characteristics between intermetatarsal neuroma and control groups by foot affected

		Case (IMN present) <i>n</i> = 68		Control (No IMN) <i>n</i> = 32		<i>p</i> value
		Mean ± SD	Range	Mean ± SD	Range	
IMN right foot <i>n</i> = 40	FPI	3.5 ± 2.9	5 to 8	2.7 ± 2.5	3 to 7	0.210
	ADF	5.33 ± 3.99	0 to 15	10.90 ± 3.62	0 to 20	<0.001
IMN left foot <i>n</i> = 38	FPI	2.9 ± 2.8	1 to 7	3.0 ± 2.9	5 to 8	0.870
	ADF	4.10 ± 3.89	0 to 15	11.30 ± 3.14	2 to 18	<0.001

IMN Intermetatarsal neuroma, FPI Foot Posture Index, ADF Ankle dorsiflexion (degrees)

P values from independent *t* test comparison of cases with controls. Note there is some overlap in cases as some subjects have IMN in both feet

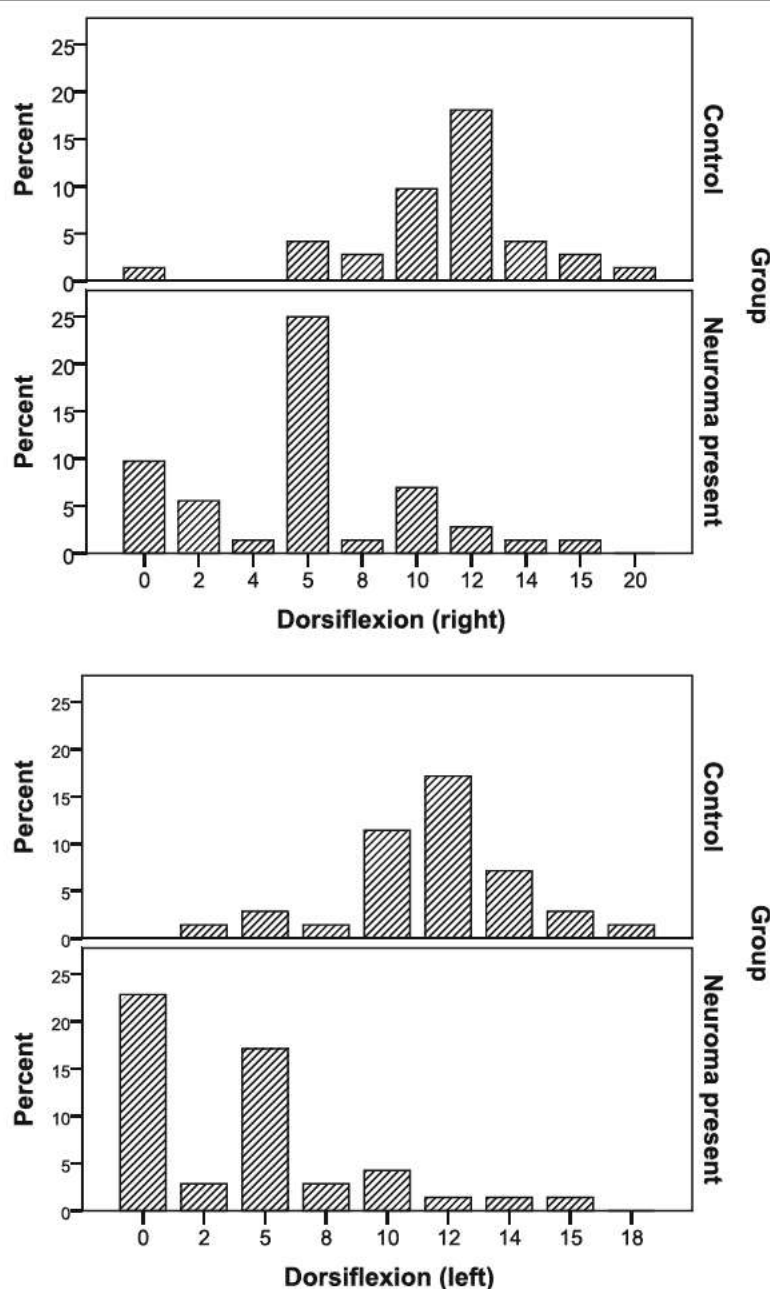


Fig. 2 Graph of ankle dorsiflexion in degrees for intermetatarsal neuroma and control groups *left and right feet*

Table 2 Description of intermetatarsal neuroma by foot and the interspace(s) affected

Interspace	Right foot	Left foot	Both feet	Total
2/3	14	9	5	28 (41.2%)
3/4	12	8	3	23 (33.8%)
Both	3	11	3	17 (25.0%)
Total	29 (42.6%)	28 (41.2%)	11 (16.2%)	68

Total interspaces affected: right foot ($n = 40$); left foot ($n = 38$)

differ across interspace groups ($p = 0.80$ on the right and $p = 0.79$). Logistic regression models, adjusted for age, sex, FPI and BMI, estimated that the odds of having an intermetatarsal neuroma in the right foot decreased by 38% (OR 0.62; 95% CI 0.51–0.76) with each additional degree of ankle dorsiflexion, and in the left foot by 30% (OR 0.70; 95% CI 0.59–0.82) (Table 4). Alternatively, these odds ratios can be expressed for each degree of reduction in ankle dorsiflexion as 1.61 (95% CI 1.32–1.96) for the right foot and 1.43 (95% CI 1.22–1.69) for the left foot. That is, the odds of having a neuroma increased

Table 3 The relationship between the affected interspaces and foot posture index and ankle dorsiflexion

Interspace	Right foot			Left foot		
	n	FPI mean $\pm$ SD median (range)	ADF mean $\pm$ SD median (range)	n	FPI mean $\pm$ SD median (range)	ADF mean $\pm$ SD median (range)
2/3	19	3.2 $\pm$ 2.6 4 (3 to 7)	4.63 $\pm$ 2.87 5 (0 to 12)	13	2.7 $\pm$ 1.9 3 (0 to 5)	3.62 $\pm$ 3.84 2 (0 to 10)
3/4	15	3.2 $\pm$ 3.5 3 (5 to 8)	5.87 $\pm$ 4.66 5 (0 to 14)	11	2.9 $\pm$ 2.8 3 (1 to 7)	4.55 $\pm$ 4.25 5 (0 to 12)
Both	6	5.2 $\pm$ 1.7 5 (3 to 8)	6.17 $\pm$ 5.49 5 (0 to 15)	14	3.6 $\pm$ 2.5 4 (1 to 6)	3.86 $\pm$ 5.10 2.5 (0 to 15)
<i>p</i> value		0.27	0.80		0.47	0.79

p value from Kruskal Wallis one way analysis of variance test (non parametric test)

by 61 and 43% for the right and left feet, respectively, with each degree of reduction in ankle dorsiflexion.

In summary, there were no significant differences in FPI between IMN interspaces affected or between cases and controls. The IMN subjects had a significant decrease in ankle dorsiflexion measurements compared with control subjects.

Discussion

This study used the FPI to investigate for an association between foot posture and IMN. The results showed no association between foot posture and IMN formation. Our mean FPI values were slightly less than the normative value of +4 reported by Redmond et al., who measured FPI on 619 healthy subjects [38]. The mean FPI scores in our study were 3.5 ± 2.9 (range -5 to 8) for the right-foot IMN and 2.9 ± 2.8 (range -1 to 7) for the left-foot IMN which based on our sample size is not significantly different to our controls ($p = 0.21$ and $p = 0.87$ respectively). Hagedorn et al. also in the Framingham population study did not find any association between foot posture and IMN [21].

Most of the literature states that the third interspace is more commonly affected with IMN for anatomical and biomechanical reasons [4, 6, 9, 25, 39]. Keh et al. [40]

reported a slightly increased occurrence of neuroma in the second interspace, but an equal distribution of neuroma in both interspaces was reported by Mann et al. [5]. In this study approximately 41% occurred in the second interspace only, 34% in the third interspace only and 25% in both interspaces (Table 3). We did not find any relationship between FPI and IMN in a particular interspace. Therefore, the belief that IMN would more commonly occur in the third interspace in a more pronated foot as a result of hypermobility of the lateral column relative to the medial column cannot be supported by these findings. Furthermore, even though the second interspace was the most frequently affected site, cavus foot posture was not associated with formation of IMN in the second interspace.

It is reasonable to assume that individuals with a high BMI would have increased pressure in the forefoot during the propulsive phase of gait, which may traumatize plantar interspace nerves. However, in our study, there was no significant difference in mean BMI between IMN and control groups. The Johnston County study reported that there was no clear association between BMI and the presence of foot deformities [41]. However, in a systematic review by Butterworth et al., a significant association between foot pain as a result of non-specific foot disorders and increasing BMI was reported [42]. While obesity has been linked to an increase in plantar pressure measurements [43], which can lead to a more pronated foot and increase in foot pain [44, 45], in our case-control series no relationship between BMI and IMN formation was established.

A number of authors state that a lack of ankle dorsiflexion in gait increases pressure of the forefoot [10, 11, 34, 35, 46]. Barrett went as far as to recommend endoscopic gastrocnemius release as a treatment for IMN patients exhibiting ankle equinus [35]. DiGiovanni et al. studied the effect of isolated gastrocnemius tightness in a group of 34 patients with forefoot and midfoot pain versus a control group of 34 without any foot or ankle pain. In his study he used

Table 4 Multivariable logistic regression estimates of odds of one or two intermetatarsal neuromas

Variable	Right foot		Left foot	
	OR (95% CI)	<i>p</i> value	OR (95% CI)	<i>p</i> value
Age (years)	1.06 (0.99, 1.14)	0.75	0.99 (0.94, 1.04)	0.75
BMI (kg/m ²)	0.88 (0.73, 1.06)	0.20	1.09 (0.96, 1.24)	0.20
Female ^a	2.08 (0.34, 12.8)	0.95	0.96 (0.23, 4.03)	0.95
FPI	1.29 (0.93, 1.81)	0.85	1.02 (0.82, 1.27)	0.85
ADF (degrees)	0.62 (0.51, 0.76)	<0.001	0.70 (0.59, 0.82)	<0.001

BMI Body mass index

FPI Foot Posture index

ADF Ankle dorsiflexion (degrees)

OR Odds ratio, CI Confidence interval

^aCompared to male. Other ORs are per unit increase

an equinometer to measure ankle dorsiflexion and defined equinus as less than 5°, and found that in the patient group, there was a twofold higher rate of equinus compared to the control group. The study, however, did not have any patients with IMN and only seven subjects were diagnosed with metatarsalgia of non-neurological origin. Although the measurement technique used in our study has been reported in the literature as unreliable [47, 48] the intra-rater reliability was found to be high.

One limitation of this study was that FPI is a static measurement and may not represent a subject's dynamic function during gait given that IMN symptoms occur mostly during the propulsive phase of gait. However, some studies support the use of FPI as a valid tool in predicting dynamic function of the foot during gait [49, 50]. Secondly, gender imbalance may have affected the results, as 82% of the study subjects were female. However, there were no significant differences in mean ankle dorsiflexion measurements between male and female subjects. Presentation of IMN is more commonly seen in women, and their rate of hospital admission is three times higher than that of males in Australia [1].

Conclusion

This study examined the relationship of FPI, BMI and ankle dorsiflexion with IMN and to the author's best knowledge is the only case-control study of this type in the literature. No relationship was found between foot type, BMI or IMN; nor was there an association between the FPI and the interspaces affected by IMN. However, there was a strong association between the presence of IMN and a restriction of ankle dorsiflexion. The authors suggest that future studies investigate the effect of the management of ankle equinus on IMN treatment.

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Availability of data and materials

All data has been kept in a locked cabinet within the Podiatric Medicine Unit/ University of Western Australia. The author can be contacted directly should there be any need to access the data if required.

Authors' contributions

RN with guidance of AB and LS S wrote the study protocol. RN designed the data collection forms, performed data collection and drafted the manuscript. RN and ABre conducted the statistical analysis. All authors were involved with interpretation of data and critical revision of the manuscript. All authors read and approved the final manuscript.

Competing interests

The authors declare that they have no competing interests.

Consent for publication

Consent was obtained from participants with regards to publishing the results of the study in a scientific journal and also to present these at conferences and meetings.

Ethics approval and consent to participate

Ethics approval was obtained by the University of Western Australia's human ethics committee (project number RA/4/1/2543). All subjects were given patient information and gave written informed consent for taking part in the study.

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Appendix 3

Radiographic Analysis of Feet With and Without Morton's Neuroma

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Abstract

Background: The aim of this research was to investigate the association of various structural measurements of the forefoot with Morton's neuroma (MN).

Methods: Weightbearing anteroposterior and lateral foot radiographs of subjects attending the University of Western Australia (UWA) Podiatry Clinic and the first author's private practice were included in this study. A single assessor measured the following angles: lateral intermetatarsal angle (LIMA), intermetatarsal angle (IMA), hallux valgus angle (HVA), digital divergence between the second and third digits (DD23), digital divergence between the third and fourth digits (DD34) and relative metatarsal lengths of the first to fifth metatarsals (Met1-5), and the effect of MN size as measured by ultrasonograph on digital divergence. Intratester reliability of all radiographic measurements was assessed on all radiographic measurements. The study included 101 subjects, of whom 69 were diagnosed with MN and 32 were control subjects without MN. The mean ($\pm$ standard deviation) age of MN subjects was 52 ($\pm$ 15) years and for control subjects, 48 ($\pm$ 12) years.

Results: When comparing all feet, there were no significant differences in the LIMA, HVA, IMA, digital divergence angles and the relative metatarsal distances between subjects with MN and control subjects. No relationship between MN size and digital divergence was found in either foot, or in either neuroma location.

Conclusion: We were unable to demonstrate any relationship in this study between radiographic metatarsal length and angular measurements in a symptomatic MN group compared to a control group. In addition, we did not find any correlation between the size of MN as measured from ultrasonographic images and radiographic evidence of digital divergence.

Level of Evidence: Level III, case control study.

Keywords: Morton's neuroma, metatarsal length, radiographic measurements, digital divergence

Introduction

Morton's neuroma (MN) is a painful condition in the forefoot caused by swelling of the common digital plantar nerve to the affected interspaces.³⁶ Most literature indicates the nerve enlarges and becomes fibrosed as a result of repetitive trauma.^{1,21,32,45} The diagnosis of MN has traditionally been based on clinical signs and symptoms. Pastides et al in a prospective study of 36 patients with histopathology-confirmed diagnosis of MN found Mulder's click to be the most sensitive clinical sign (98%).³¹ In recent years, physicians often use the imaging modalities of MRI and ultrasonography to confirm the diagnosis. According to a recent systematic review, ultrasonography was more accurate than MRI in diagnosing MN with 90% sensitivity and 88% specificity.⁴⁶

Injury to the nerve has been attributed to foot morphology,² ankle equinus,³ and possibly the relative metatarsal lengths.³⁰ Recently, metatarsal shortening osteotomies have been recommended to decompress MN.^{4,30} Morton believed the

symptoms associated with the condition were probably the result of having a short first metatarsal that caused an overload of the lesser metatarsals, thus traumatizing the common digital nerve.²⁷ Patients with short and hypermobile first rays are observed to have higher plantar pressures beneath the second metatarsal, leading to transfer metatarsalgia.^{17,34} Other factors are also discussed in the literature, such as the presence of

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Table 1. The Interspaces Affected With Morton's Neuroma for Right, Left, and Both Feet.

	2/3 Interspace	3/4 Interspace	Both Interspaces	Total
Right foot only	13	12	0	25
Left foot only	12	13	8	33
Both feet	4	1	6	11
Total	29	26	14	69
Right foot total	17	13	6	36
Left foot total	16	14	14	44

hallux valgus deformity and dorsiflexed first ray.^{19,42,44} These potentially increase the pressure under the lesser metatarsal heads, which may lead to MN formation.

One phenomenon that can be seen radiographically in the assessment of patients with MN is digital divergence. This can conceivably occur as a result of enlargement of the bursa-neuroma complex, which may place pressure at the base of the affected proximal phalanges.^{18,25,39} Digital divergence can also be seen in other pathologies such as digital contractures and plantar plate ruptures, which are normally ruled out as differential diagnoses when assessing MN. Grace et al did not find any relationship between MN and digital divergence.¹⁸ However, their study did not include data on the size of the neuromas or on the interspaces that were affected by the divergences.

There are no published studies that compare MN patients with control subjects in terms of the metatarsal parabola and radiographic measurement. The aim of this research was to evaluate various structural measures in the forefoot of patients with MN.

Methods

Weightbearing anteroposterior (AP) and lateral foot radiographs of subjects attending the University of Western Australia (UWA) Podiatry Clinic as well as R.N.'s private practice were used in this study. One hundred and one subjects (69 with MN diagnoses and 32 controls) were recruited to the study, which was part of a larger research project investigating the etiology of MN. This research project was approved by the Human Research Ethics Committee of UWA (File reference no. RA/4/1/2543). All participants consented to the use of their radiographs for this study. The mean ($\pm$ standard deviation) age of MN subjects was 52 (± 15) years and for control subjects, 48 (± 12) years. The 69 MN subjects had 80 affected feet; the right foot was affected in 36 subjects and the left foot in 44 subjects. The number of interspaces affected for both right and left feet of MN subjects is shown in Table 1.

Inclusion criteria for MN subjects were a minimum of 6-month history of neuroma symptoms, a clinically demonstrated painful Mulder's click with ultrasonographic

confirmation of MN. Ultrasonographic diagnosis of MN was made by an experienced musculoskeletal radiologist and assessed on both transverse and longitudinal axes as an abnormal ovoid hypoechoic thickening corresponding to the location of maximum tenderness.¹¹ Each MN subject was clinically examined by the corresponding author and by an experienced musculoskeletal radiologist to rule out any other source of pain such as capsulitis and lesser metatarsal phalangeal joint instability such as plantar plate pathology. The inclusion criterion for control subjects was a negative history of MN or neuroma-like pain in the forefoot. Exclusion criteria for both neuroma and control groups were any previous history of surgery to the lower extremity, any proximal nerve entrapment at the level of the ankle, knee, hip, or back; any history of significant trauma to the forefoot area (including plantar plate pathology); metatarsus adductus greater than 15°; any difficulty in walking or standing; diabetes; or a history of systemic arthritis.

A single assessor performed the radiographic measurements for each patient using standard weightbearing AP and lateral radiographs. The following angles were measured: lateral intermetatarsal angle (LIMA), intermetatarsal angle (IMA), hallux valgus angle (HVA), digital divergence between the second and third digits (DD23), digital divergence between the third and fourth digits (DD34), and relative metatarsal lengths of the first to fifth metatarsals (Met1-5). All radiographic measurements were performed via an IntelViewer System computer program (<http://www.intelerad.com/en/products/inteleviewer/>). Intratester reliability of all radiographic measurements was assessed on radiographs from 5 randomly selected subjects. These were reassessed 1 week after the initial measurements had been made and established the test-retest reliability of the radiographic measurements used in the study.

The LIMA was determined from the weightbearing lateral radiograph by placing a tangential line over the central portion of the dorsal cortex of the first and second metatarsal shafts. The angle between the 2 tangential lines was measured as described by Bryant et al (Figure 1).⁷ If the lines diverged distally the value was positive, and if the lines converged it was given a negative value.

The HVA angle was formed by bisecting the proximal phalanx and the first metatarsal, and measured as described by Gerbert (Figure 2).¹⁶ The IMA was formed by the bisection of the first and second metatarsal (Figure 2).

The digital divergence angles (DD23 and DD34) were formed by bisecting the proximal phalanges of the second, third, and fourth digits. The angles between these bisection lines were measured to assess the relative divergence of the digits on the affected interspaces (Figure 3).

The relative metatarsal distances were measured by using the Maestro technique (Figure 4).²⁴ The reliability of this measurement technique has been favorably reported in the

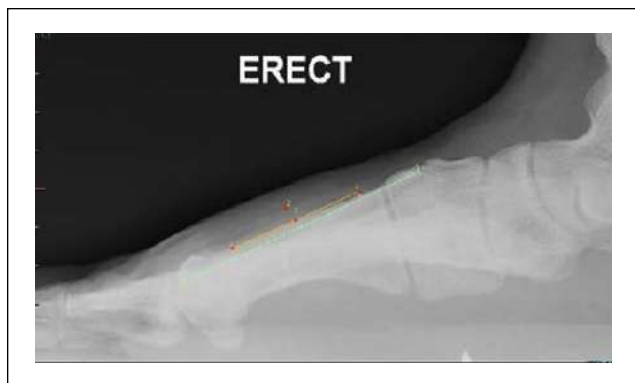


Figure 1. Radiograph demonstrating Lateral intermetatarsal angle (LIMA).



Figure 2. Hallux valgus and intermetatarsal angles.

literature.¹² First, the M1 axis, defined as the “axis of the foot,” was drawn from the midpoint of the medial talar head to the distal lateral aspect of the calcaneocuboid joint. Next the SM1 line was drawn perpendicular to the M1 axis such that it bisected the fibular sesamoid. A line was then drawn parallel to the SM1 line tangentially to the apex of the head of the second metatarsal called the SM2 line. The purpose of having SM2 was to measure the distance of all metatarsals



Figure 3. DD23 and DD34 measurements. DD23, digital divergence between the second and third digits; DD34, digital divergence between the third and fourth digits.

relative to the second metatarsal. The relative length of each metatarsal was the measurement of the perpendicular line drawn from the apex of each metatarsal to the SM2. If the perpendicular line was above SM2, the value was assigned as negative, whereas if below, a positive value was given.

The intraclass correlation coefficient (ICC) for the LIMA, IMA, DD23, and DD34 angles and the metatarsal distance measurements ranged between 0.95 and 0.99, values that are considered to be excellent.³³

The size of MN was based on measurements from the transverse ultrasonographic image as reported by radiology reports. Only participants with a transverse view measurement were included in this study.

Data were entered into Microsoft Excel and exported to IBM SPSS Statistics v23 for analyses. Independent sample *t* tests were used to compare the angle and distance measurements between the MN and control groups. Right and left feet were analyzed separately to ensure data were independent. In addition, metatarsal length measurements of subjects with single neuromas were compared to those of control subjects. For these analyses,



Figure 4. Maestro technique to assess relative metatarsal lengths.

as well as distinguishing between right and left feet, the second and third interspaces were evaluated separately. Mann-Whitney *U* tests (MWU) were performed to take into account the reduced sample sizes and the non-normality of the distributions of some of the measurements. Spearman rank correlation coefficients were used to assess relationships between neuroma size and digital divergence. Feet with both the 2/3 and 3/4 interspaces affected were not included as increased divergence in one interspace may have affected the divergence in the adjacent interspace.

As insufficient data were available before this study to allow sample size calculations, retrospective power calculations were conducted using PS: Power and Sample Size Calculation.¹⁵ No mathematical correction was made for testing multiple associations. Instead, all results including 95% confidence intervals and *P* values <.05 are reported.

Results

When comparing all feet, there were no significant differences in the LIMA, HVA, IMA, digital divergence angles, and the relative metatarsal distances between subjects with MN and control subjects (Table 2).

Second Interspace Measurement Comparison

In the left foot there was a significant difference in the IMAs of the MN subjects compared to the control subjects (mean 10.7 vs 8.2, MWU *P* = .02; Table 3). In the right foot there was a significant difference in the mean of the fifth metatarsal length of the MN subjects compared to control subjects (mean 3.1 vs 2.7, MWU *P* = .01). In the left foot the DD34 angles of the MN and control subjects differed significantly (mean 2.0 vs 4.1, MWU *P* = .02), and in the right foot similar differences were seen (mean 0.9 vs 4.4, MWU *P* < .001).

Third Interspace Measurement Comparison

In the left foot there was a significant difference in the Met4 of the MN subjects compared with the control subjects (mean 1.3 vs 1.5, MWU *P* = .02; Table 3). Similarly, in the right foot the Met3 and Met4 lengths of the MN and control subjects differed significantly (mean 0.4 vs 0.5, MWU *P* = .03, and mean 1.1 vs 1.3, MWU *P* = .02, respectively).

The average MN size was 7.5 mm (range 3-12 mm) in transverse section as measured on ultrasonograph. No relationship between MN size and digital divergence was found in either foot, or in either neuroma location (Table 4).

Discussion

Metatarsal shortening osteotomy for “decompression” of MN was introduced by Park et al in 2013.³⁰ They retrospectively compared the outcomes for deep transverse metatarsal ligament (DTML) release in 46 MN patients with those of 40 MN patients who underwent both DTML release and shortening of a lesser metatarsal using a Weil osteotomy. In their preoperative evaluation of patients, metatarsal lengths were measured according to the technique described by Maestro et al. A Weil shortening osteotomy was performed on the longer metatarsal adjacent to the affected interspace. Outcomes were measured using the Foot Function Index and the American Orthopaedic Foot & Ankle Society Forefoot Score. The outcomes for the group that received DTML release with Weil osteotomy were significantly better than those of the group that received DTML release only. There are no published case-control studies that evaluated the relative metatarsal lengths of patients with MN compared to a control group. We therefore undertook this study using the radiographic measurements described by Maestro et al in order to explore the validity of performing a lesser metatarsal osteotomy for MN. We found no significant differences in the relative lengths of metatarsals between the feet of MN and control subjects. However, some unusual findings were made for the single interspace comparisons with controls. These may be due to chance, however, and due to the relatively small sample size.

Table 2. Comparison of Radiographic Measurements Between MN and Control Groups by Foot Affected.

	MN (L) (n = 43)	Control (L) (n = 32)	P Value ^a (95% CI)	MN (R) (n = 37)	Control (R) (n = 32)	P Value ^a (95% CI)
LIMA	0.3 ± 3.0	-0.2 ± 2.1	0.45 (-0.77, 1.72)	0.6 ± 1.9	0.1 ± 2.2	0.26 (0.44, 1.57)
HVA	13.4 ± 7.2	11.3 ± 7.2	0.28 (-1.78, 5.94)	13.0 ± 9.1	10.6 ± 7.1	0.22 (-1.50, 6.41)
IMA	9.6 ± 3.3	8.2 ± 2.5	0.05 (-0.02, 2.76)	8.6 ± 3.1	8.0 ± 2.8	0.40 (-0.82, 2.00)
DD23	7.7 ± 6.0	5.6 ± 4.5	0.07 (-0.33, 4.68)	7.0 ± 5.1	5.1 ± 4.7	0.11 (-0.45, 4.26)
DD34	3.6 ± 3.9	4.1 ± 3.7	0.60 (-2.25, 1.32)	3.0 ± 3.7	4.4 ± 4.0	0.15 (-3.18, 0.52)
Met1	0.3 ± 0.2	0.2 ± 0.6	0.66 (-0.14, 0.23)	0.2 ± 0.4	0.3 ± 0.3	0.59 (-0.20, 0.11)
Met3	0.5 ± 0.2	0.6 ± 0.2	0.64 (-0.11, 0.07)	0.5 ± 0.2	0.5 ± 0.2	0.49 (-0.06, 0.13)
Met4	1.4 ± 0.4	1.5 ± 0.2	0.45 (-0.18, 0.08)	1.4 ± 0.4	1.3 ± 0.3	0.45 (-0.09, 0.21)
Met5	2.9 ± 0.5	2.9 ± 0.3	0.88 (-0.19, 0.17)	2.9 ± 0.5	2.7 ± 0.3	0.16 (-0.05, 0.33)

Abbreviations: MN, Morton's neuroma; L, left; R, right; CI, confidence interval; LIMA, lateral intermetatarsal angle (degrees); HVA, hallux valgus angle (degrees); IMA, first and second intermetatarsal angle (degrees); DD23, digital divergence between second and third toes (degrees); DD34, digital divergence between third and fourth toes (degrees); Met1, relative first metatarsal length (cm); Met3, relative third metatarsal length (cm); Met4, relative fourth metatarsal length (cm); Met5, relative fifth metatarsal length (cm);

^aP value reported by independent sample t tests.

Table 3. Comparison of Radiographic Measurements in Subjects With MN in the Second and Third Interspaces, Right and Left Foot (see Table 2 for Control Values).

	2/3L (n = 16)	P Value MWU (95% CI)	2/3R (n = 17)	P Value (95% CI)	3/4L (n = 14)	P Value (95% CI)	3/4R (n = 12)	P Value (95% CI)
LIMA	-0.3 ± 4.3	0.24 (-1.94, 1.72)	1.0 ± 1.9	0.17 (-2.22, 0.36)	0.3 ± 1.6	0.30 (-0.82, 1.71)	-0.1 ± 2.3	0.59 (-1.31, 1.69)
HVA	15.2 ± 9.7	0.12 (-1.12, 8.83)	15.0 ± 8.5	0.09 (-9.01, 0.13)	11.7 ± 5.5	0.77 (-3.92, 4.78)	12.4 ± 10.2	0.90 (-7.30, 3.65)
IMA	10.7 ± 3.5	0.02 (0.70, 4.25)	8.7 ± 2.4	0.42 (-2.31, 0.90)	8.8 ± 2.3	0.70 (-1.05, 2.12)	9.1 ± 4.1	0.63 (-3.28, 1.05)
DD23	9.0 ± 7.2	0.05 (-0.67, 7.46)	7.6 ± 4.7	0.11 (-5.33, 0.32)	4.9 ± 4.6	0.62 (-3.54, 2.30)	4.9 ± 4.2	0.74 (-2.90, 3.32)
DD34	2.0 ± 2.7	0.02 (-4.1, 0.05)	0.9 ± 2.9	0.001 (1.29, 5.70)	4.7 ± 4.7	0.85 (-1.99, 3.23)	6.4 ± 3.0	0.07 (-4.60, 0.51)
Met1	0.3 ± 0.2	0.61 (-1.9, 0.39)	0.1 ± 0.3	0.10 (-0.41, 0.35)	0.3 ± 0.1	0.90 (-0.24, 0.37)	0.3 ± 0.3	0.57 (-0.26, 0.15)
Met3	0.5 ± 0.2	0.45 (-0.12, 0.10)	0.6 ± 0.2	0.10 (-0.20, 0.01)	0.4 ± 0.2	0.07 (-0.23, 0)	0.4 ± 0.2	0.03 (-0.02, 0.21)
Met4	1.5 ± 0.3	0.98 (-0.11, 0.21)	1.5 ± 0.3	0.05 (-0.36, -0.02)	1.3 ± 0.3	0.02 (-0.35, 0)	1.1 ± 0.3	0.02 (0.02, 0.38)
Met5	3.0 ± 0.5	0.40 (-0.11, 0.35)	3.1 ± 0.4	0.01 (-0.53, -0.13)	2.7 ± 0.5	0.17 (-0.38, 0.08)	2.5 ± 0.4	0.08 (0.05, 0.47)

Abbreviations: 2/3L, second interspace mean and standard deviation left foot; 2/3R, second interspace mean and standard deviation right foot; 3/4L, third interspace mean and standard deviation, left foot; 3/4R, third interspace mean and standard deviation right foot; CI, confidence interval; MWU, Mann-Whitney U test.

Table 4. Correlation Between MN Size and Digital Divergence.

Foot	Position	n	r	P Value
Right	2/3	13	0.370	0.21
	3/4	11	0.135	0.69
Left	2/3	12	0.184	0.57
	3/4	12	-0.047	0.88

Menz et al evaluated relative metatarsal lengths using the Maestro technique in older people with forefoot pain (n = 40) and in a control group of older patients with no forefoot complaint (n = 70).²⁶ They found no association between pain in the forefoot and relative metatarsal lengths. However, using a MatScan system they found the peak plantar pressure under metatarsals 3 to 5 was significantly higher compared to the control group. They also observed a weak negative correlation between pressure in the forefoot and metatarsal length. Patients with forefoot pain were

selected on a subjective basis and none had a confirmed diagnosis of MN. The increase in pressure under the lesser metatarsals in this elderly group can perhaps be explained by fat pad atrophy and stiffness of the forefoot.^{9,23}

Kaipel et al²² did not find any relationship between increased metatarsal length and plantar pressure in 91 patients with and without forefoot pain. They prospectively followed 2 groups of patients (51 feet in each group) with and without metatarsalgia, measured the relative metatarsal lengths using the Maestro et al technique, and performed plantar pressure measurements on an EMED-SF1 platform. These workers reported that relative metatarsal length had no effect on peak pressure or peak force. Their findings question the rationale of performing shortening osteotomies such as Weil osteotomy for the management of metatarsalgia.

Morton was the first to propose that hypermobility of the first ray resulting from a short first metatarsal and/or dorsal extension of the first metatarsal can lead to the lateral transfer of load to metatarsals 2 to 5.^{27,28} This phenomenon,

known as “first ray insufficiency,”^{8,42} can lead to increased pressure in the lesser metatarsal area, and Morton suggested this could predispose to MN formation.^{10,42,43} Breusch et al reported MN development following Wilson osteotomy, which significantly shortens the first metatarsal.⁶ Bauer et al also reported that short length of the first metatarsal is a risk factor for recurrence of MN after open neurectomies.⁴ However, using a technique first described by Hardy and Clapham, Grebing and Coughlin measured the relative difference in lengths of the first and second metatarsals for 46 control, 53 hallux valgus, 54 hallux rigidus, and 49 MN patients. They found no correlation between shortness of the first metatarsal and hypermobility of the first ray in all groups investigated.¹⁰ Similarly, our study found no significant difference between the MN and control groups with regard to the first metatarsal lengths or the relative lengths of the first and second metatarsals. Collectively, these findings question Morton’s belief that short first metatarsals cause MN formation.

Measurement of the LIMA was used to evaluate the relationship between first ray dorsiflexion and MN formation. We used the LIMA to determine whether the dorsal cortex of the first metatarsal was more elevated in relation to the second metatarsal on weightbearing lateral view of subjects. In our study, even though the first metatarsal was more elevated in the MN group the differences were not statistically significant. Roukis reported LIMA measurements of MN patients ($n = 50$) and compared them to a group of patients with hallux rigidus, hallux valgus, and plantar fasciitis.³⁵ He found that LIMA in the hallux rigidus group was significantly greater than in other groups, including MN. Horton et al also measured first ray elevation using a different technique in 3 groups of patients with hallux rigidus ($n = 146$), asymptomatic controls ($n = 50$) and MN group ($n = 64$).²⁰ They reported no difference between the groups with respect to elevation of the first metatarsal head. Based on the review of the literature and on our present findings, a significant relationship between MN and first ray dorsiflexion cannot be demonstrated.

A limitation of measuring the LIMA is that the weight-bearing lateral view depicts the foot during midstance.²⁰ The pathological forces in MN are most likely caused during propulsion when maximum force is applied to the forefoot. During initial and final propulsion, strong forces are applied to the metatarsal heads.¹⁴ Future studies should investigate radiographically the change in first ray dorsiflexion from midstance through propulsion in order to assess the role of the first ray in transferring load to the forefoot.

Lateral shifting of the hallux and increases in the IMA have been described as possible causes of forefoot symptoms.^{6,19,26,40,41,44} Dietze et al performed a radio-kinematic and pedobarographic study and found that in 8 patients with HVA and first ray instability, there was a

significant increase in force transfer to metatarsals 2 to 4.¹³ This transfer of force may cause overload to the forefoot and result in MN formation. Waldecker studied the plantar loading patterns in 50 patients with hallux valgus (HV) and metatarsalgia and in 50 patients with HV and no forefoot symptoms.⁴⁴ He found a significant increase in peak pressure from medial to lateral across the forefoot in patients with HV and forefoot pain. He explained this load transfer as a possible lack of the windlass mechanism which can occur as a result of increase in hallux valgus and increase in varus rotation of the first ray. In our study, we compared the HVAs and IMAs between the MN and control groups and found no significant differences.

To our knowledge, the only case control study on digital divergence was published in 1993 by Grace et al.³⁷ These workers did not find a significant increase in digital divergence in MN subjects ($n = 48$) compared to normal subjects ($n = 100$). Their study did not state the size of the neuromas, nor did they report the divergence angles of the second and third interspaces separately. We found no significant differences in the DD23 and DD34 angles between MN and control groups. Based on the data available, we found no correlation between size of the MN and digital divergence.

One limitation of our study relates to statistical power. Retrospective calculations indicate the study had a power between 0.54 and 0.78 to detect differences of 2 mm in Met measurements, and a minimum power of 0.83 to detect a difference of 5 degrees in angle measurements when all MN and control subjects were compared. However, for the single interspace and digital divergence analyses, the sample size and hence statistical power was reduced. Another limitation of our study may be that females were approximately twice as frequent in our MN group. However, this represents the normal demographic presentation of MN as indicated by the 3-fold higher rate of hospital admission for MN among females in Australia compared to males.²⁹ Another potential limitation is the use of 2-dimensional weightbearing AP radiographs when examining the metatarsal length. It would also be important to assess sagittal plane measurements of metatarsals when investigating increased pressure of the forefoot as an etiology of MN, as suggested by Bauer et al.⁴ Future studies could conceivably measure coronal images of the transverse arch to assess the relative height of the metatarsals relative to the ground. As recommended by some statisticians,^{5,38} no statistical correction was made for multiple testing and instead all results are reported. Thus, some of the significant associations observed here could be due to chance.

Conclusion

In conclusion, we were unable to demonstrate any relationship between metatarsal length and MN formation in symptomatic MN patients compared to a control group. Therefore,

based on these results and in the absence of an irregular lesser metatarsal parabola, it is difficult to justify metatarsal shortening procedures as a routine surgical treatment of MN. Furthermore, we found no correlation between the sizes of MN estimated using ultrasound images and radiographic evidence of digital divergence. Lastly, we found no relationship between first ray dorsiflexion or shortness of the first metatarsal and presence of MN, which questions the validity of Morton's early thoughts on the etiology of MN.

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