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REVIEW ARTICLE

The dysmorphic metatarsal parabola in diabetes—clinical examination and management: a narrative review

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Foot posture and function is important in diabetes, particularly as neuropathy in diabetes may present with motor in addition to sensory neural deficits. Examination of the anatomical architecture of the foot can inform on its load-bearing and balancing function. An examination that does not feature in guidelines on assessment of the diabetic foot is that of assessing whether a metatarsal parabola is present or malformed. The metatarsal 'parabola' (in the transverse plane) is so called because the cascade of the differing lengths of the metatarsals form a parabola, defined as the intersection of an arc with a flat (plantar) surface. The parabola serves a function in the rollover motion or forefoot rocker of the foot before heel rise to provide stability and balance in static stance. A further function ensures that the lever-action at the first metatarsophalangeal joint takes place with dorsiflexion of the hallux. This narrative review summarises the literature regarding methods of measuring the metatarsal parabola, dysfunction of the foot due to a dysmorphic metatarsal parabola, clinical relevance, examination and management in diabetes care. It documents the short first metatarsal (SFM) as a risk factor for diabetic foot ulceration. Examination for identification and management of dysmorphic metatarsal parabolae is recommended for foot examinations in diabetes care.

Keywords: brachymetatarsia, custom orthosis, foot examination, metatarsalgia, Morton's extension, podiatry, prescription innersole, SFM, shoe insert, short first metatarsal

Introduction

Lower limb amputations in diabetes can be traced back to a foot lesion, which, if untreated, can progress to an ulcer and consequent morbidity.[1] A clear link between diabetic neuropathy, increased plantar pressure, formation of callus and ulceration has been shown.[1–3] Prevention of plantar foot ulceration is paramount, to prevent lower limb amputations and reduce the resultant socioeconomic burden.[4,5] Global and local guidelines on the management of diabetes note that callus formation develops in response to pressure and/or friction and should be referred to a podiatrist or specialist foot team for removal, investigation of aetiology and prevention of recurrence.[4–9]

Foot posture is important in diabetes, particularly as the person with diabetes complicated by peripheral neuropathy may present with motor neuropathy in addition to sensory neural deficits. Examination of anatomical components of the foot can offer insight into the architecture that enables or disables the load-bearing and balancing function of the human foot. One such examination (which has not yet featured in guidelines on assessment of the diabetic foot) is that of determining the presence or absence of a functional metatarsal parabola.

The metatarsal 'parabola' is so called becaus the cascade of the differing lengths of the metatarsals as they touch the plantar surface forms a parabola, defined as the intersection of an arc with a flat surface. The parabola serves a function in the rollover motion or forefoot rocker of the foot before heel rise and provides stability and balance in standing. A further function ensures that the lever-action at the first metatarsophalangeal joint (MTPJ-1) takes place, i.e. that the hallux (big or great toe, plural 'halluces') can dorsiflex, enabling the foot venous pump mechanism.

An example of an incomplete metatarsal parabola is one in which there is either brachymetatarsia of the first metatarsal (short first metatarsal or SFM or 'Index minus foot'), or a longer first metatarsal ('Index plus foot') such that the medial arc of the parabola (formed by the lesser metatarsophalangeal joints) does not pass through the first metatarsophalangeal joint, as shown in Figure 1.

Measurement methods used to define the metatarsal parabola

Studies that have looked at the relative lengths of all metatarsals have explored the measurement of the 'metatarsal parabola'.[10,11] Methods for measuring metatarsal lengths may utilise X-ray examinations, direct bone measurements and clinical palpation. X-ray examinations are costly, require primary care patients to travel to X-ray facilities, result in absence from work and decreased productivity, and involve ionising radiation exposure. Studies have shown that palpation-based methods are simple, cheap and non-invasive, in addition to having a high degree of reliability.[12,13]

Figures 2 and 3 illustrate the different radiographic measurement approaches taken by studies over a period of more than 80 years. The approach by Fleischer, based on Nilsson's measurement method,[14] gave rise to the measurement techniques of Maestro and Barroco used by some orthopaedic surgeons.[15–17]

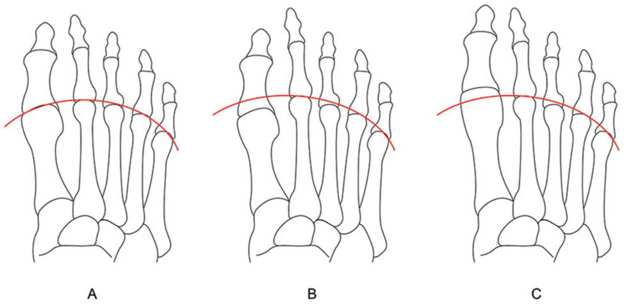

Figure 1: Balanced parabola, short first metatarsal, long first metatarsal.

Clinical relevance of SFM in diabetes care: formation of callus

Despite controversy as to whether 3 mm or 4 mm shorter quantifies or defines the shortness to be termed a 'short first metatarsal',[12,20] the relevance to diabetes care is the resultant formation of callus that can lead to diabetic foot ulceration (DFU) and the complications thereof.

Imbalance in load distribution, poor foot alignment: callus formation

One study found that variations in the length of the first and second metatarsals (metatarsal protrusion) could alter foot alignment during stance.[22] A later study on the role of the first metatarsal and hallux in balance showed that malfunction of the hallux in flexion would interfere with balance and thus cause pressure shifting in the foot (Figure 4).[22] This is particularly important in diabetes care because pressure shifting can cause callus. Balance deterioration could also be present in plantar sensory dysfunction.[23–25]

Disruption of the windlass mechanism, altered foot posture and increased pressure: callus formation

SFM can disrupt the windlass mechanism of the first metatarsophalangeal joint (MTPJ-1) and affect foot posture.[26–28] One common compensation when the MTP-1 joint cannot flex is the flexion moment passing to the interphalangeal joint of the hallux. This increased pressure provides a diagnostic clue in the form of transfer hyperkeratosis on the medial and plantar surface of the proximal IPJ-1 and phalanx of the hallux. These are common sites of hallux ulceration in diabetes.

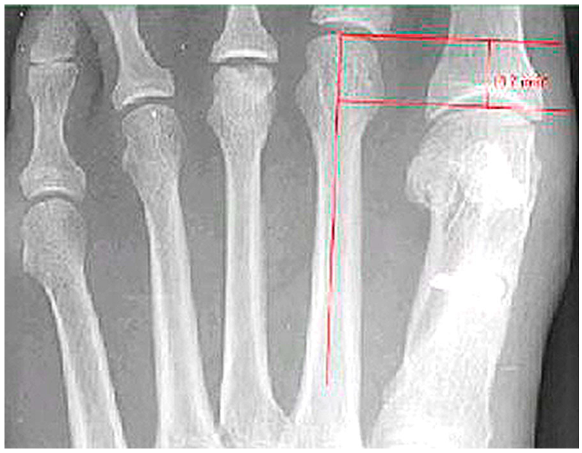

Figure 3: Nilsonne metatarsal protrusion index.[14]

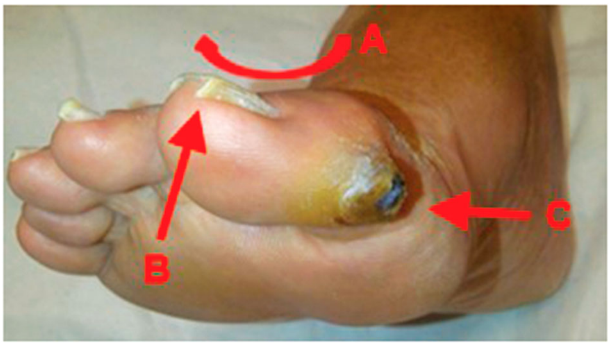

Figure 4: Medial pressure shifting and upturned proximal hallux phalanx in SFM (note medial pressure is also causing the involuted nail). Source: author.

Joint stresses and instability, uneven plantar pressure: ball of the foot callus formation

The metatarsal parabola functions to provide stability during the stance and propulsive portion of gait, as weight is transferred to the metatarsal heads.[18] Morton's concept of lateral movement of pressure states that, if the first metatarsal is too short, it cannot assume the body weight in a balanced way and thus compensatory changes in foot posture might occur.[18] A study found that patients with a Morton's toe registered higher pressures beneath the second metatarsal (mean of 320 kPa) compared with a non-Morton foot control group (mean 243 kPa).[29] A further study found that 60% of patients

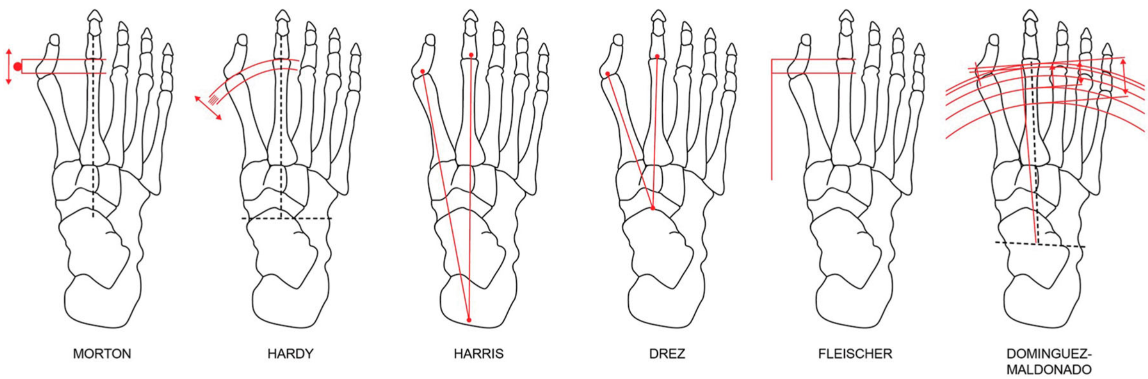

Figure 2: Approaches to measurement of first metatarsal relative length (re-drawn) Morton[18] 1935, Harris[19] 1949, Hardy[20] 1951, Drez[21] 1980, Dominguez-Maldonado[10] 2014 and Fleischer[14] 2017.

who presented with metatarsalgia (ball-of-the-foot pain) displayed lesser metatarsophalangeal joint instability.[30] One study considered that the cause of lesser metatarsophalangeal joint symptoms was a deficit in first ray weight-bearing.[31] In a critical analysis of Morton's concepts, a review found support for Morton's notion that weight can shift laterally in individuals who have a short first ray.[32]

SFM is therefore commonly found in conjunction with metatarsalgia, plantar hyperkeratosis (callus on the plantar surface of the foot) and plantar heloma durum (corn on the plantar surface of the foot)[33] as the lesser metatarsal heads assume the body weight, with resultant overlying formation of callus (hyperkeratosis) and/or corns (helomata dura).

Hyper-dorsiflexion of proximal joint of the hallux: callus formation under the hallux

Compensation for the lack of flexion at the MTP-1 joint may result in hyper-dorsiflexion of the distal hallucal phalanx. The resultant jamming of the articular surfaces at MTPJ-1 (first metatarsophalangeal joint, i.e. ball joint of the big toe) can result in limitation of joint range of motion and lead to the condition called functional hallux limitus, or, as the condition progresses, hallux rigidus. The 'jamming' of the articular surfaces of the first metatarsal and the proximal phalanx may give rise to articular capsule thickening of the MTPJ-1, often mistaken by patients as a 'bunion' or hallux valgus (Figure 5).

Altered gait, abduction of the forefoot: transfer callus formation under MTPJ-2 or MTPJ-5

Another compensation of altered gait could be the abduction of the foot in order to shift the fulcrum laterally over the second metatarsal head, leading to callus and helomata (corn) formation over MTPJ-2 (second metatarsophalangeal joint, i.e. ball joint of the second toe) due to overload of this lesser metatarsal structure. Similarly, abduction can increase supinatory forces, leading to callus formation over MTPJ-5 (fifth metatarsophalangeal joint, i.e. ball joint of the fifth toe)(Figure 6).

Altered gait, abduction of the forefoot: increased risk of bunion formation

Compensatory abductory movement of the forefoot, combined with rotation over the second metatarsal, may increase pronatory rotational forces over the first metatarsal head. This may increase the risk of hallux valgus (bunion) formation in a foot at risk of hallux valgus (due to other inherent and hereditary anatomical risk factors such as rounded articular facets).[34]

Figure 5: (A) enlarged MTP-1 Joint, (B) upturned hallux at proximal phalanx, (C) callus on medial border of distal phalanx of the hallux.
Source: author.

Restricted windlass: increased risk of acquired flatfoot

Lack of a functioning fulcrum at MTPJ-1 will restrict the windlass mechanism, as previously described.[35] The windlass mechanism forms the primary part of the sagittal plane foot function, stability and propulsive gait. A restricted windlass mechanism may be implicated in the development of acquired pes planus.

Although SFM may be implicated in the development of such pathologies as acquired pes planus, hallux valgus, hallux limitus and hallux rigidus, an investigation into the precise relationship of SFM and these latter pathologies is outside the scope of this study.

Dysfunctional windlass: poor venous return from the ball of the foot

Importantly, extrapolating from what is now known regarding the interlinked windlass mechanism (via hallux dorsiflexion) and the foot venous pump,[36–38] a non-functioning windlass will impact negatively on foot venous return.

It must be noted that the windlass mechanism, activated by hallux dorsiflexion, is also severely impaired by the wearing of inflexible or rigid soled footwear that inhibits the necessary flexion at the ball of the foot.

Clinical examination and non-surgical management in resource-limited diabetes care

Palpation method for measurement of metatarsal head positions

In podiatry, the clinical palpation technique is taught to identify, inter alia, the position of the metatarsal heads. The simple approach is a plantar palpation and marking method (Figure 7). The validity and reliability of the dorsal palpation technique when compared with radiographic measures has

Figure 6: Overload at proximal phalanges of the halluces and over the MTP-5 joints.
Source: author.

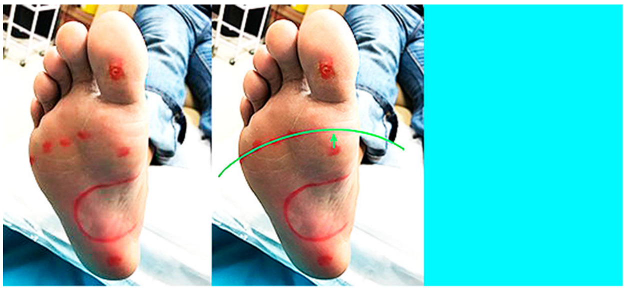

Figure 7: Plantar palpation and marking of metatarsal heads (centres of joint capsules) to confirm first metatarsal brachymetatarsia.

been established.[13] A further study established intra-observer reliability of measuring first and second metatarsal protrusion by means of dorsal palpation.[12] This obviates the need for expensive and time-consuming radiographs in a resource-limited diabetes care setting.

As noted in Figure 7, the metatarsal parabola is dysmorphic, hence tension on the joint results in limited flexion of the hallux, with compensatory callus on the distal IPJ (first joint of the big toe). Heel pain may be present due to increased torsion on the plantar fascia in an abducted foot posture.

A high risk (2–5 times) of plantar plate pathology of the second metatarsophalangeal joint has been associated with shortness of the first metatarsal greater than 4 mm relative to the length of the second metatarsal.[14]

Prevalence in a KwaZulu-Natal sample diabetic population

Studies suggest different prevalence figures of SFM/Index minus/Morton's foot in different populations.[14,19,21] It is not well documented whether patients with diabetes who present with transfer callus on the lesser metatarsophalangeal joints may also present with a short first metatarsal (SFM). However, in a sample of 301 patients with diabetes examined by metatarsal palpation in KwaZulu-Natal, South Africa,[38] the frequency of SFM with hyperkeratosis was 24.6% ($n = 74$) for the right foot and 24.3% for the left foot ($n = 73$ excludes an amputee), as shown in see Table 1.

Podiatric non-surgical treatment modalities

Dudley J Morton (not to be confused with Thomas G Morton after whom the condition known as Morton's neuroma in the foot is named) recorded and measured brachymetatarsia, which he termed a 'short first metatarsal' (SFM).[18] As treatment, Morton suggested the use of a 'compensating insole' containing a platform beneath the head of the short first metatarsal,

Table 1: Frequencies of SFM and signs of MTPJ-1 dysfunction in diabetes[38]

Signs of MTPJ-1 pathology ($n = 301$)	Frequency right foot (%)	Frequency left foot (%)
Short first metatarsal (SFM)	24.6	24.3
Hallux abducto valgus (HAV)	8.0	8.3
Prominent MTPJ-1 (pathognomonic of SFM, hallux limitus, hallux rigidus)	28.6	28.2
Hyperkeratosis (corns and callus)	36.2	36.2

Figure 8: Medial, plantar and dorsal views of a custom prescription innersole as used in conservative treatment of SFM with heel pain caused by torsional strain on the plantar fascia.

which would extend the length of the hallux.[18] This is similar to the construction method employed by South African-trained podiatrists, in which the extension pad (or 'Morton's extension') may not necessarily extend the entire length of the hallux (Figure 8).

Corrective metatarsal surgery is not undertaken lightly in a patient living with diabetes. Surgery would elongate the first metatarsal by means of distraction osteogenesis or may shorten the diaphysis of the longer second metatarsal.[39,40] In contrast, podiatrists gradually remove the dermal hyperkeratosis by non-invasive sharp debridement followed by low-speed dermabrasion. This is followed by a clinical biomechanical examination. The podiatrist will thereafter construct a functional in-shoe device to correct the faulty foot biomechanics. The orthosis or prescription innersole is worn inside suitably flexible footwear (Figure 8). Prescription inserts are usually affixed with Velcro® as this enables the insert to be removed and re-positioned in different pairs of a patient's footwear.

The hallux extension component serves to move the fulcrum of the first metatarsophalangeal joint distally and restore the lever arm of the first ray to the hallux,[41] while the kinetic wedge excavation creates a deep 'pocket' for the first metatarsophalangeal joint. This overcomes the tension on the joint and allows it to flex.

Implications for clinical practice

All members of the multidisciplinary team in resource-limited diabetes care can learn to observe the location of callus. Palpation and skin mapping of the metatarsal heads to establish the presence of a complete or dysmorphic metatarsal parabola can be taught. This is particularly important as patients with diabetic neuropathy may not present with protective pain preceding ulceration. Paper mapping via the Harris Mat system (foot imprinter) or Diaped® or Podotrack® foot impression paper can enable patient education, awareness of the role of podiatry and improved comprehension of flexible footwear and footwear insert guidelines.

Discussion

Compensatory abduction with hyper-pronation due to a dysmorphic curve in the metatarsal parabola is implicated in the reduction or loss of hallux dorsiflexion in gait.[42]

Many studies have supported the biomechanical effect of either a long or short first metatarsal in the aetiology of forefoot pathology such as functional hallux limitus, hallux rigidus, forefoot plantar pressure, Morton's neuroma, abductory dysfunction resulting in functional pes planus and the potential for calcaneal enthesitis due to torsional forces acting on the plantar fascia or aponeurosis.[43–50]

We are unaware of any other studies documenting the SFM as a risk factor for callus formation and thus diabetic foot ulceration. Since almost a quarter of the patients with diabetes examined in a South African 2019 study presented with SFM with callus, we suggest that this should be considered a risk factor for DFU.[38] As such, we recommend that manual examination for identification and management of dysmorphic metatarsal parabolae should form part of foot examinations in diabetes care.

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