

Diabetic foot ulceration: the implication of biomechanics on prevention and treatment

Laura Barr

Lower-limb biomechanical dysfunction and structural deformity are major contributing factors to the development of diabetic foot ulceration. Comprehensive biomechanical assessment and appropriate orthotic intervention should be key elements in the treatment of the diabetic patient, particularly those with a moderate to active risk stratification. There are several common biomechanical deficits associated with the foot in diabetes. This article outlines a variety of these biomechanical issues and demonstrates resulting areas of ulceration associated with these deficits. The use of orthoses during the healing period will be discussed, with suggestions for reasonable orthotic intervention in the long term to reduce the risk of recurrence and facilitate prevention.

The foot acts as the foundation of the erect human body — its intrinsic structure and positioning can either directly or indirectly influence all joints of the lower limb, pelvis and spine. As the first point of sensory contact and force transmission upon weight bearing, the foot also provides vital sensory and proprioceptive feedback to the central nervous system during all phases of gait (Pradels et al, 2013). Effective gait relies on the ability of joints, muscles, tendons and ligaments to react to changes in extrinsic moments during mobility. Similarly, when considering variances in ground interface, qualitative characteristics of cutaneous and adipose tissues are required to sustain non-pathological, lower-limb function (Yavuzer et al, 2006).

Population studies in the UK and The Netherlands have shown diabetes to be associated with a 5% lifetime risk and 2% annual risk of foot ulceration (Boulton et al, 2005). Recurrences are documented as greater than 50% at 3 years; a significant risk factor for limb amputation and mortality (Boulton et al, 2005). It is unsurprising, therefore, that World Health Organization

statistics estimating a rise in current diabetes diagnoses of nearly 50% across Europe since 2000 (Sawacha et al, 2010) are of particular concern for health services. Consequently, identification and treatment of risk factors for foot ulceration are a primary concern for those healthcare professionals working within the field of diabetes management.

It is widely documented that deformation and alteration to biomechanical foot function is a predisposing factor for ulceration of the diabetic foot (Crawford et al 2007; Boulton et al 2008; Formosa et al 2013) and, as such, comprehensive, accurate mechanical assessment and treatment is required for at-risk feet. Indeed, current National Institute for Health and Care Excellence (NICE, 2011) and Scottish Intercollegiate Guidelines Network (SIGN, 2010) diabetic foot care guidance specifies that treatment for those presenting with risk factors be inclusive of assessment for appropriate footwear and orthoses, of which it is assumed biomechanical assessment is a prerequisite.

In order to most effectively treat the at-risk diabetic foot, be that with consideration to

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Article points

1. Biomechanical assessment of the foot and ankle is important in order to identify potential risk factors for the diabetic foot.
2. Diabetes is associated with several commonly identifiable functional and structural foot deformities.
3. Appropriate orthotic intervention in short-term and long-term foot care should be taken in response to biomechanical assessment for individual patients.

Key words

- Biomechanics
- Orthoses
- Ulcer prevention

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ulceration prevention, resolution or recurrence, it is imperative that mechanical characteristics of the individual foot be identified and addressed within the treatment plan. Recent literature has challenged traditionally accepted aetiology relating to neuropathic foot shape and function, specifically that supinated (high arch) foot posture (*Figure 1*) occurs due to atrophy of the intrinsic musculature. In 2011, Bokan documented that a high arched supinated foot position was associated with 80% of patients due to reduced common peroneal nerve conduction and atrophy of those associated muscles. This finding was in direct contrast to Garcia-Alvarez et al's (2013) research, which found a higher prevalence of pronated foot posture (*Figure 2*) among people with diabetes, irrespective of the presence or extent of polyneuropathy.

Research relating to the biomechanical properties of the lower limb in diabetes regularly focuses on aetiology and predictive elements for future ulceration risk. Unfortunately, although several common factors have been identified (e.g. reduced range of motion at the first metatarsophalangeal joint, claw toes, equinus of the midfoot, equinus of the hind foot, and reduced range of motion at the talocrural joint (Lazaro-Martinez et al, 2014), there is little consensus regarding the consistency of predicting progression of foot disease related to these mechanical components, and uncertainty about causation as a consequence of natural disease history or the presence of mechanical features before the development of diabetes.

From a clinical perspective, this conflict serves only to highlight the presence of vastly diverse lower-limb anatomy within the population with diabetes, and reinforces the requirement that assessment and orthotic treatment planning for every patient be tailored and specific to the individual.

Common biomechanical deficits: presentation, functional effect and orthotic intervention

Diabetes is associated with several commonly identifiable functional and structural foot

Figure 1. Feet described as having a supinated foot posture are generally associated with a laterally deviated subtalar joint axis, resulting in greater external net supination moments than pronation moments around the subtalar joint on loading.



Figure 2. Feet described as having a pronated foot posture are generally associated with a medially deviated subtalar joint axis, resulting in greater external net pronation moments than supination moments around the subtalar joint on loading.



deformities. These may exist in isolation or combination and result in a predisposition to ulceration in particular areas of the foot. Although the following features by no means form an exhaustive list, having an appreciation for the basic biomechanical deficits listed

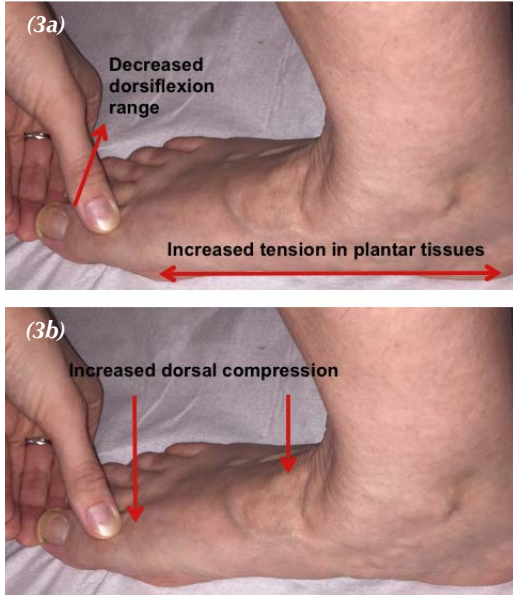


Figure 3. (a) Functional hallux limitus: when the foot is under load, increased tension in the plantar soft tissues result in decreased passive dorsiflexion range, and (b) associated compression in the dorsal aspect.

Figure 4. Common pattern of plantar ulceration associated with limitation at the first metatarsophalangeal.

Hallux limitus
Hallux limitus refers to reduced range of motion at the first metatarsophalangeal (MTP) joint. In gait, the first MTP joint is required to dorsiflex at heel-off into terminal stance to facilitate propulsion in the sagittal plane; a motion termed the third rocker of gait (Dananberg, 2000). Limitations are considered to be functional if

here will bring the clinician a greater understanding of the principles involved with orthotic treatment.

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Functional hallux limitus has an implication in the development of osteoarthritis at the first MTP joint, and early subchondral sclerosis is often identifiable on plain film radiographs prior to the development of reduced passive range of motion at the joint (Becerro de Bengoa Vallejo et al, 2014). Several modalities have been described as contributing to functional hallux limitus. Dorsiflexion of the first ray at mid stance causes mechanical jamming of the articular surfaces at the first metatarsal and proximal phalanx. This joint limitation is thought to be perpetuated in the diabetic foot due to thickening of the plantar structures articulating distal to the first MTP joint. The plantar aponeurosis and flexor hallucis longus tendon are both found to display increased thickness in those patients with diabetes (Bolton et al, 2005) a trend of which increases with severity of diabetes (Giacomozzi et al, 2005), resulting in increased tensile strain in the plantar structures during gait.

In the general population, as with the diabetic population, functional hallux limitus is also typically associated with a medially deviated subtalar joint axis, whereby the foot is subject to higher extrinsic pronation moments and resultant increased rate of midfoot collapse throughout the stance phase of gait (Kirby, 2001). Given the effect on full foot function relating to this mechanism, as tensile forces

increase in the plantar aspect under load, so too do opposing compressive forces: not only at the first MTP joint, but also dorsal midfoot interosseous compression (*Figure 3*). Although few data exist regarding bone density of the midfoot and forefoot related to diabetes, one report found a 13% decrease in bone mineral density in the calcanei of people with diabetes (Sinacore et al, 2008). As such, it is not unreasonable to suggest this trend may also be present in other bones of the foot and that compression could be considered as a potential fracture risk.

Limited range of motion at the first MTP joint has been described as a statistically significant factor for the development of ulceration (Turner et al, 2007). Due to the mechanical deficit described, ulceration may typically occur as a result of increased peak pressure at the distal plantar aspect of the hallux at propulsion, or due to shear at the lesser metatarsal heads associated with compensatory abduction of the forefoot at late stance (*Figure 4*).

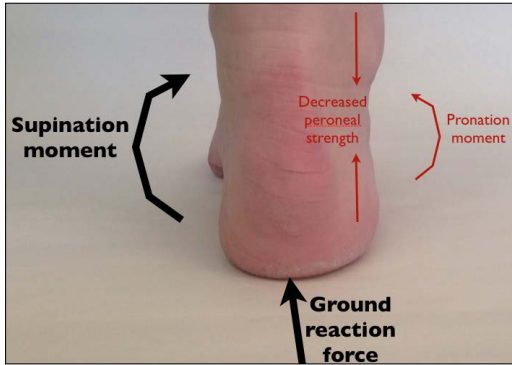
During healing, the aim of orthotic intervention should relate to the reduction of pressure over the ulcerated areas by reducing the rate at which those areas are loaded in gait and by eliminating shear.

In the instance of plantar ulceration due to hallux limitus, the use of non-removable casts, walkers (IWGDF, 2015), or removable forefoot offloading orthoses (Cavanagh et al, 2010) in conjunction with appropriate gait training to arrest stance phase prior to heel rise, are some of several possible treatment options that will appropriately account for the biomechanical deficit and facilitate healing. With regard to long-term prevention of occurrence or recurrence, the use of custom foot orthoses (insoles) may be sufficient to achieve rotational equilibrium, reduce tensile plantar and compressive dorsal forces, and maximise available dorsiflexion range of motion at the first MTP joint (Hall et al, 2004). In the presence of other deformation, structural hallux limitus or hallux rigidus, the use of bespoke footwear and sole adaptations, such as forefoot rockers and forefoot stiffeners, may be required

Figure 5. Ulceration risk: common pattern of plantar hyperkeratosis associated with hammer and claw toe deformities.



Figure 6. Demonstration of the internal and external forces acting on the supinated foot, resulting in higher net supination than pronation turning moments.



in combination with foot orthoses in order to optimise biomechanical function.

Toe deformities

Claw or hammer toe deformities are widely considered to be a common cause for ulceration at the distal end of the second to fifth digits (Figure 5). Although this is a common presentation within the neuropathic diabetic foot, the aetiology of deformation development remains unclear. The presence of distal neuropathy has been significantly associated with a reduction in lean muscle mass and increased adipose volume of the intrinsic foot muscles (Bus et al 2002; 2009; Anderson et al, 2004). Despite this well-documented occurrence, no significant link has yet been demonstrated relating this to the development of toe deformities.

Regardless of pathogenesis, the development of ulceration as a result of such toe positions is commonly seen in diabetic foot clinics due to loading of pressure intolerant distal aspects of the toes in gait, and associated addition of dorsal forces generated by the toe box of ill-fitting footwear.

During healing, similar principles apply as to that of hallux limitus. An offloading orthosis should be designed to reduce the duration of ground reaction force acting at the toe end in the sagittal plane. Forefoot offloading orthoses and forefoot rocker orthoses are both appropriate for achieving this aim (Cavanagh et al, 2010), the application of which should also include an open or malleable dorsal forefoot design in order to simultaneously reduce dorsal forces over the toes. Definitive orthoses to assist in the prevention of ulcer occurrence or recurrence will typically involve the use of bespoke footwear to accommodate for toe deformation and resist the application of dorsal force, in conjunction with forefoot rocker sole adaptations and foot orthoses to address the sagittal plane biomechanics and reduce peak plantar pressure (Arts et al, 2015).

Forefoot alignment and midtarsal range of motion

In the non-pathological foot, the midtarsal joints are found to be multi-axial, displaying motion in all spatial planes (Nester et al, 2014). As described previously, medial deviation of the subtalar joint axis can cause increased midfoot

Figure 7. (a) Inverted forefoot alignment in the coronal plane (b) resulting in increased load to the plantar aspect of the fifth metatarsal head.



motion and associated soft tissue tensile and compressive issues at the latter stages of gait, resulting in a propensity to ulceration in the medial plantar column. Conversely, lateral deviation of the subtalar joint axis is associated with decreased midfoot motion in gait, resulting in increased loading to the lateral column and increased risk of associated lateral forefoot ulceration of the diabetic foot (Kim et al, 2015). In conjunction with a trend of reduced nerve conduction velocity in the peroneal nerve in relation to diabetic neuropathy (Bokan et al, 2011), a high net supination moment occurs throughout stance; as the internal pronation moment produced by peroneus brevis and longus decreases, and external supination moment produced by the ground reaction force acting medial to the subtalar joint axis increases (*Figure 6*). Through time this loading pattern in stance phase can progress to limitations in passive range of motion at the midtarsal joint, such as a resting inverted forefoot alignment in the coronal plane (*Figure 7a*), and forefoot equinus in the sagittal plane, further increasing load and risk of ulceration to the lateral plantar aspect underlying the fifth metatarsal head (*Figure 7b*).

During the healing period, the primary biomechanical objective should be attainment of rotational equilibrium in the coronal plane to reduce the duration of load over the ulcer site. For feet that display a suitable passive range

of motion at the subtalar and midtarsal joints, the use of offloading orthoses with a wide heel base or lateral heel flare can assist in extending the lever arm at initial contact and loading, to counteract supination moments. For those less flexible deformities, the use of customised orthoses such as a total contact cast or custom insole integrated within a therapeutic walker boot, may provide greater benefit (Cavanagh et al, 2010). The use of orthoses for ulcer prevention have the same biomechanical objectives that, dependent on individual assessment (inclusive of joint flexibility, tissue integrity and pressure tolerance), may be achieved by the use of custom foot orthoses in conjunction with bespoke footwear or footwear adaptations.

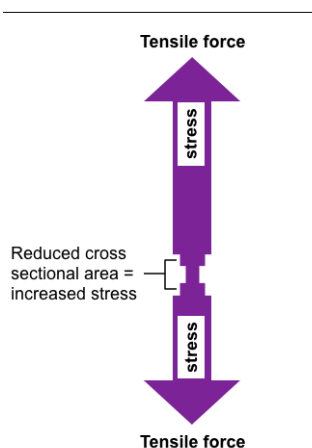
Talocrural joint limitation

Multiple studies have shown significance regarding the reduction of talocrural joint range of motion corresponding to the presence of diabetic peripheral neuropathy (Zimney et al, 2004; Giacomozzi et al, 2005; Turner et al, 2007), a phenomenon likely to be perpetuated by thickening of the Achilles tendon in the same patient group (Oliveira et al, 2011). With reduced dorsiflexion range at the talocrural joint being associated with an elevated risk of forefoot ulceration due to early heel rise causing increased loading at the forefoot, and progressive neuropathy associated with Achilles tendon rupture (Zakaria et al, 2014), identification of this deficit during biomechanical assessment is vital for both long and short-term treatment.

Similarly, the impact of midfoot equinus has been shown to adversely affect talocrural joint function due to inducing dorsiflexion of the ankle in relaxed stance: an alignment associated with increased stress in the Achilles tendon, and dorsal impingement in gait (Dananberg, 2000)

Excluding traumatic force, Achilles tendon rupture can occur as a result of increased intrinsic stress in areas of damage and narrowing of the tendon (*Figure 8*). As such, orthotic support in both the healing and prevention stages should involve reducing repetitive strain on the tendon. The use of

Figure 8. Demonstration of increased tendon stress over a damaged area of tendon.



simple heel elevators can reduce tendon stress and maximise available dorsiflexion range by accommodating an appropriate degree of plantar flexion at the talocrural joint. Incorporation of this elevation within custom foot orthoses can also address combined underlying biomechanical issues if identified during assessment.

Conclusion

Biomechanical assessment and treatment planning can aid ulcer resolution and assist in the reduction of ulcer recurrence. Care should be taken to assess and account for each component of biomechanical deficit in order to maximise both short- and long-term goals. Although evidence is lacking in some areas, acquiring an accurate understanding of the mechanical principles involved in lower-limb function can greatly assist the clinician in delivering positive outcomes in diabetic foot care. ■

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