# Biomechanics and choosing footwear for the diabetic foot

## Luigi Uccioli, Claudia Giacomozzi

**Article points**

1. People with diabetes may experience changes in foot posture as a result of neuropathy that lead to increased plantar pressures and increase the risk of ulceration.
2. Foot deformities arising form neuropathy or amputation result in areas of increased plantar pressure, especially at the level of the metatarsal heads.
3. Custom-made or commercially available insoles in retail shoes, or in combination with therapeutic shoes, have been proposed as methods of reducing abnormal foot pressures and thus ulceration in the diabetic foot.

**Key words:**
- Biomechanics
- Footwear
- Insole
- Therapeutic shoe

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**Changes in foot posture and architecture as a result of diabetic neuropathy impact on the normal biomechanics of walking and weight bearing in the foot. The increased plantar pressures associated with these changes contribute to the risk of ulceration. In this review, the authors explore the biomechanics of the foot during walking, and the impact of footwear on these processes. Biomechanical alterations commonly seen in the diabetic foot are described, and recommendations for footwear are made, based on the person with diabetes' level of risk of ulceration.**

Changes in the biomechanics of the foot, resulting in pressure distribution, are known risk factors for ulceration of the diabetic foot. Footwear is the most common intervention for biomechanical abnormalities of the foot. Custom-made or commercially available insoles in retail shoes, or in combination with therapeutic shoes, have been proposed as methods of reducing abnormal foot pressures and thus ulceration in the diabetic foot.

An understanding of the contrast between normal foot biomechanics and the changes seen as a result of diabetic neuropathy – and its impact on risk of ulceration – is instructive for those involved in the management of the diabetic foot. The role of footwear in ulcer prevention at all levels of diabetic foot ulcer risk is also discussed.

### Biomechanics of the foot

Natural human gait results in the progression of the whole body due to the acceleration of the centre of mass in all the three directions of space: forward, vertically (up and down) and horizontally (side to side). A combination of internal and external forces are needed to accelerate and decelerate the body mass: internal forces are provided by muscle action, external forces are mainly due to gravity (Zatsiorsky, 2002).

Ground reaction force (GRF) refers to the force exerted by the ground on a body in contact with it; a person standing on the ground exerts a force on it (equal to the person's weight) and at the same time an equal and opposite GRF is exerted by the ground on the person. The evolution of GRF during walking is usually investigaited with respect to its three components: vertical, anterior–posterior, and medio–lateral (*Figure 1a–c*). For the purpose of comparison, body weight is normalised ([force value/body weight] × 100) and the various components expressed as a percentage of body weight. Below is a brief overview of force actions on a healthy foot during barefoot walking at a self-selected speed (Zatsiorsky, 2002).

### Vertical force

At heel strike, the vertical component of force (VCF) rises steeply from zero to almost body weight. At the point at which the foot is flat, the body mass is moving downwards and landing on the leg. To decelerate this downward motion, and at the same time to support the body weight, a force larger than body weight is necessarily applied to the foot. Physiological VCF at this phase of stance ranges from 110–120% of body weight. The role of the foot as a shock absorber is crucial in this phase to prevent damage to its own structures, as well as the bones and joints that transmit forces from the foot up the leg and to the trunk and head. In a healthy individual, this shock absorption is obtained by an internal rotation of the tibia through the ankle and subtalar joints, inducing a certain pronation of the foot and an unlocking of the main rear- and mid-foot joints.

At mid-stance the leg is almost vertical and the motion of the centre of mass of the body is in an upward arch. Usually VCF at mid-stance ranges from 70–80% of body weight. Mid-stance is the phase during which the largest area of the foot is simultaneously in contact with the ground and consequently local plantar pressures are quite low. However, rotation of the tibia over the talus starts to

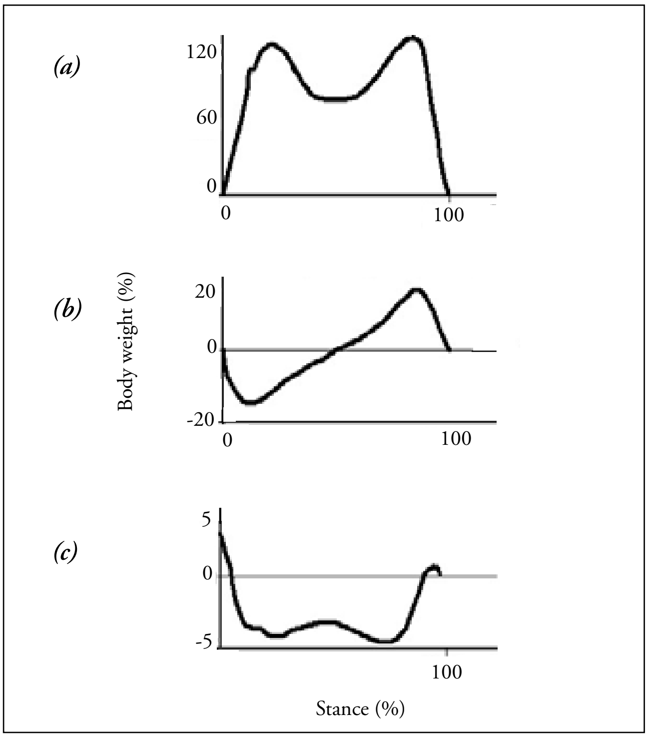


*Figure 1a–c. Generalised graphical representations of the (a) vertical, (b) anterior–posterior and (c) medio–lateral force components of barefoot walking in a healthy person.*

**Page points**

1. While standing still on smooth surfaces is possible, locomotion is impossible without friction; to move the body forward an equal and opposite force must be delivered by the ground.
2. An investigation of the biomechanics of the foot are informative in understanding how changes to the foot's structure are associated with the risk of ulceration in the diabetic foot.
3. Motor neuropathy is responsible for a progressive atrophy of the intrinsic muscles of the foot that may result in a variety of foot deformities.
4. Limited joint mobility contributes to the onset of increased plantar pressures associated with ulceration.

invert the foot motion in the frontal plane. Foot supination begins, together with the locking of the rear-, mid- and fore-foot joints. The foot gradually becomes a rigid lever, with a high and rigid longitudinal arch supporting the expected forward propulsion.

At heel raise – the beginning of propulsion – the whole body is accelerated forward and VCF increases to some 120% of body weight. This represents the second peak of the VCF curve pattern. Finally, at toe-off, VCF returns to zero through the sudden offloading of the foot.

### Friction

While standing still on smooth surfaces is possible, locomotion is impossible without friction; to move the body forward an equal and opposite force must be delivered by the ground. The intensity and direction of the forces continuously change during walking, but remain in the horizontal plane. The resulting horizontal force vector is usually analysed with respect to an anterior–posterior component force (ACF; *Figure 1b*) that is aligned with the line of progression of the whole body, and a medio–lateral component force (MCF; *Figure 1c*) that is perpendicular to the ACF.

During landing, a forward acceleration occurs that generates a backward ACF, with a maximum force that corresponds to the complete load acceptance; during propulsion a backward acceleration occurs, and a corresponding forward ACF is generated by the ground. In a barefoot gait, the absolute maximum ACF reached during landing is 20% of body weight, as well as the maximum ACF during propulsion. ACF is zero at mid-stance. The curve in *Figure 1b* shows the negative and positive periods of ACF, these should be equal to maintain an overall constant forward velocity from step to step. If the negative portion is wider than the positive one, the whole body tends to slow down; conversely, the body tends to accelerate forward if the positive portion is wider than the negative one.

MCF is usually of a smaller magnitude than ACF, with a maximum value not usually greater than 5% of body weight.

## Biomechanical alterations common to the diabetic foot

An investigation of the biomechanics of the foot are informative in understanding how changes to the foot's structure, and the resultant alterations in gait, are associated with the risk of ulceration in the diabetic foot.

Motor neuropathy is responsible for a progressive atrophy of the intrinsic muscles of the foot that may result in a variety of foot deformities, including hammer or claw toes, hallux valgus and prominent metatarsal heads. These deformities of the foot result in areas of increased plantar pressure and among people with diabetes are known to increase the risk of foot ulceration (Ledoux, 2008).

Limited joint mobility, especially at the ankle and at the first metatarsal joints, contributes to the onset of increased plantar pressures associated with ulceration. Limited joint mobility in all planes and directions of movement can be read as a consequence of stiffness at those joints which mainly manage the foot–floor interaction during gait. In turn, increased stiffness at the ankle and first metatarsal joint interferes with the correct foot loading pattern, preventing the correct downloading of the metatarsal heads during push-off. The poor inversion/eversion movement confines the progression to the sagittal plane. As a result, the metatarsal heads undergo a greater and longer loading, which may contribute to the onset of ulceration (Giacomozzi, 2003).

Some people with diabetes are known to have increased thicknesses of the plantar fascia. A relationship between plantar fascia thickness and increased forefoot vertical forces, and thus plantar pressure, has been established. This finding supports the hypothesis that soft tissue abnormalities contribute to the development of an altered distribution of pressure under the foot (D'Ambrogi et al, 2003).

As a result of the concurrent action of all the above factors (i.e. intrinsic/extrinsic musculature imbalance, joint stiffness, thickening of tendons and ligaments) people with diabetic neuropathy may develop rigid feet that are less adaptable to the floor. In these circumstances, the foot remains rigid during the whole walking cycle, leading to high plantar pressures under the metatarsal heads (D'Ambrogi et al, 2003).

The association between biomechanical change, foot deformity and sensory neuropathy results in a foot that experiences increased plantar pressures, increased friction with footwear and lacks protective sensitivity to mechanical stress and potentially harmful objects and circumstances. Under these circumstances, the person with diabetes is at increased risk of ulceration.

## Footwear and biomechanics

Shoes interfere with the performance of natural gait, i.e. that performed by a healthy person while walking barefoot. While walking in shoes, a "normal" – rather than "natural" – gait, with the aim of moving the body forward in space while taking into account the constraints from the use of shoes, can be achieved (Rossi, 2000).

Shoe heels result in the rear-foot assuming a greater inclination with respect to the ground than is seen barefoot (*Figures 2a–b*). This elevation of the heel results in faster unloading of the rear-foot during walking, and a greater loading of the metatarsal heads. The higher the heel, the greater the alteration of the loading pattern. Increased heel height also results in a shortening of the Achilles tendon, and thus a power reduction in those leg muscles involved in propulsion. Likewise, the shoe tip is usually 1.5–3.0 cm lifted from the ground. Thus, during walking in shoes, the toes are partially prevented from taking part in propulsion, resulting in a greater involvement of the metatarsal area (Rossi, 2000).

Even more critical is the concavity of the sole under the metatarsal heads, which causes the foot as a propulsive lever to act under adverse conditions. During barefoot walking, the foot flexes more than 50 degrees at the metatarsal level, while flexion of conventional shoes ranges between 10 and 40 degrees. The less flexible the shoes, the less normal the gait. In low flexibility shoes, a flat-foot gait can be observed, with propulsion phase being focused under the metatarsal heads (Rossi, 2000).

Most conventional shoes are made with a certain flaring, while healthy feet are characterised by a longitudinal straight line. From a biomechanical point of view, this represents a constraint for the performance of the natural helicoidal movements of the foot during gait. Narrow shoes prevent the natural widening of the foot during contact with the ground, resulting in greater loading of those areas that are involved in foot–ground contact. Conversely, overly large shoes may lead to undesirable friction between foot and shoe sole. Even in well-fitted shoes the foot–ground contact may be as little as 50% of the natural barefoot footprint (Rossi, 2000).

The thicker the sole of the shoes, the more pronounced the reduction of the sensory response of the foot. This lack of tactile contact with the ground weakens the reflex action of foot and leg muscles, resulting in a less safe gait. This can be of particular concern for people at risk of falls (Rossi, 2000).

## Role of footwear in the management of the diabetic foot

In the presence of diabetic neuropathy, footwear can play a critical role in the pathogenesis of foot complications (Apelqvist et al, 1990; Macfarlane and Jeffcoate, 1997). Thus, footwear for people

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2. While walking in shoes, a "normal" gait, with the aim of moving the body forward in space while taking into account the constraints from the use of shoes, can be achieved.
3. During walking in shoes, the toes are partially prevented from taking part in propulsion, resulting in a greater involvement of the metatarsal area.

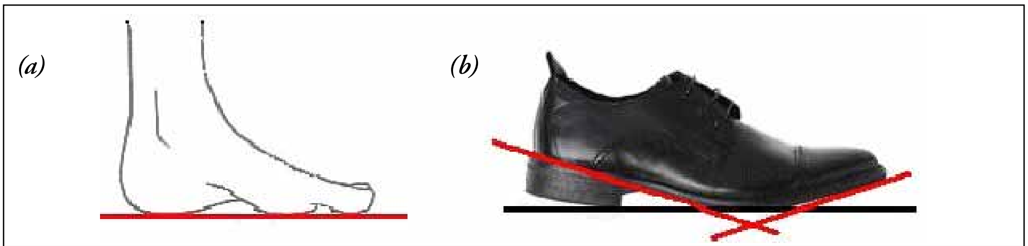
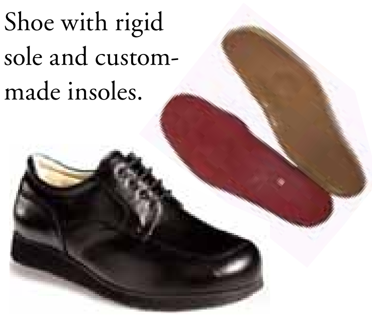



*Figure 2a–b. An illustration of the changes in foot–ground contact between (a) barefoot and (b) shoed stance. Shoe heels result in the rear-foot assuming a greater inclination with respect to the ground than is seen in barefoot stance. Lifted shoe tips partially prevents the toes from taking part in propulsion.*

Table 1. Suggestions for appropriate footwear for people with diabetes in relation to the individual's risk of ulceration (based on the University of Texas scheme [Lavery et al, 1998]).

| | LOW | MEDIUM | HIGH | VERY HIGH |
|---|---|---|---|---|
| LEVEL OF RISK | ● Normal foot sensation.<br>● No foot deformity.<br>● No history of ulceration or amputation. | ● Neuropathy.<br>● No foot deformity.<br>● No history of ulceration or amputation. | ● Neuropathy.<br>● Foot deformity.<br>● No history of ulceration or amputation. | ● Neuropathy.<br>● Foot deformity.<br>● History of ulceration or amputation. |
| ADVICE ON FOOTWEAR | | Clinicians should encourage people with diabetic neuropathy to compensate for their loss of pedal sensation by assessing socks and shoes by sight and touch for foreign objects or irregularities. Walking barefoot should be discouraged. Mended socks should avoided. | | |
| | ***Retail footwear.*** No change in footwear is necessary at this level of risk. Clinicians may encourage selection of retail footwear as described below. | ***Well-fitted retail footwear, insoles.*** People at this level of risk should be encouraged to not wear the same pair of shoes for prolonged periods. | ***Therapeutic footwear, commercial or custom-made insoles.*** | ***Therapeutic footwear, multilayered custom-made insoles.*** |
| | Retail footwear should:<br>● Be accurately measured to fit the foot and accommodate insoles in all dimensions.<br>● Have soft, preferably heat-sensitive, uppers.<br>● Incorporate soles or insoles that efficiently absorb vertical forces. | | Therapeutic footwear should include:<br>● Recessed heels.<br>● Rigid, or rigid rocker-bottom soles.<br>● A wide angle between the sole and the ground at the most anterior part of the shoe. | |
| EXAMPLES | | Laced Oxford shoe in soft leather.  | Shoe with rigid sole and custom-made insoles.  | Shoe with rigid rocker-bottom sole and a custom-made multilayered insole.  |

with diabetes should not increase the risk of complications and, ideally, also serve as a form of protection. In general, suitable footwear and insoles for people with diabetes should: (i) reduce abnormal pressure; (ii) limit the formation of callus and ulcers; and (iii) protect from external trauma (Uccioli, 2006). Furthermore, the lifestyle of the person being recommended the shoes should be taken into account, especially with regard to their level of activity (Tyrrell and Carter, 2009).

## Footwear and ulcer risk

People with diabetes, at any given time in the natural history of their condition, will experience some level of foot ulcer risk. Measures of risk usually take into account the presence or absence of protective sense perception, presence or absence of vascular disease, significant foot deformities and previous foot ulceration or amputation. One common measure of diabetic foot ulcer risk is the University of Texas classification scheme (Lavery et al, 1998). In this scheme, diabetic feet fall into one of four categories of ulcer risk: low, medium, high or very high.

The level of ulcer risk experienced by a person with diabetes should be taken into account when choosing footwear. In the following four sections, the authors provide their guidance on the types of footwear appropriate for each level of ulcer risk (summaries in *Table 1*).

### *Low risk*

People with diabetes who have normal sensation, no foot deformities and no history of ulceration or amputation can be classified as being at low risk of ulceration (Lavery et al, 1998). At low level risk, priorities should be protecting sensation and education for self-care and prevention. No real change in footwear is necessary at this level of risk. However, people in this category might be encouraged to consider the following when selecting footwear:

- Footwear that is well-fitted and wide enough in the forefoot will avoid friction that can lead to blisters, corns or callus.
- Soft, preferably heat-sensitive, uppers should be preferred for the same reasons.
- Shoe soles should be selected for their efficiency in absorbing vertical forces, thus rubber, wide and flexible soles are preferable to leather board soles.
- Tight-fitting footwear with narrow forefoot, tight toe box or tight instep should be avoided.

### *Medium risk*

The development of diabetic neuropathy, with the ensuing loss of protective sensation, places people with diabetes at

**Page points**

1. Foot deformities, frequently of the toes, often confer biomechanical changes that result in abnormal gait followed by the appearance and persistence of overloading at the metatarsal level.
2. An increased reduction in pressure can be achieved with the use of a rigid or rocker-bottom sole for people at high risk of ulceration.
3. Rocker-bottom shoes induce a modification in the walking pattern and may cause pain in the muscles at the back of the lower leg.
4. Special care should be taken using insoles in retail shoes as, if the shoe is not designed to accommodate the addition of an insole, the insertion of one will reduce the space available to the foot and increase friction.

increased risk of ulceration (Lavery et al, 1998). No prospective studies have yet satisfactorily assessed the effectiveness of footwear in primary prevention of diabetic ulceration. Despite this, clinical experience and some observational studies suggest that well-fitting shoes can play a role in protecting neuropathic diabetic feet from ulceration.

Before choosing shoes at this level of risk, the foot should be accurately measured in all its dimensions, and a shoe chosen that contains the foot (and an insole, if being used) with minimal constriction. Soft, preferably heat-sensitive, uppers should be selected. Shoe soles should be selected for their efficiency in absorbing vertical forces; rubber, wide and flexible soles are preferable to leather board soles.

Beyond footwear, the clinician can encourage those at medium risk of ulceration to compensate for their loss of pedal sensation by taking other precautions. Before putting on shoes, footwear should be assessed by sight and touch for foreign objects or irregularities. Walking barefoot, even in the home, should be discouraged. Mended socks should be avoided. People with diabetes and a medium or greater risk of ulceration should be encouraged not to wear the same pair of shoes for prolonged periods. Frequent changes of footwear result in less stress on discrete areas of skin that may ultimately reduce the risk of ulceration at that point.

### *High risk*

When the neuropathic diabetic foot is complicated by foot deformities (e.g. bunion, claw toe, hammer toe) the risk of ulceration increases (Lavery et al, 1998). Foot deformities, frequently of the toes, often confer biomechanical changes that result in abnormal gait followed by the appearance and persistence of overloading at the metatarsal level in the propulsion and toe-off phases of walking. In these areas of overload, hyperkeratosis can be followed by ulceration (Ledoux, 2008).

A recessed heel, allowing a softer impact at heel strike should be included in shoes for this group. An increased reduction in pressure can be achieved with the use of a rigid or rocker-bottom sole, which minimises the metatarsal–phalangeal joint articulation tension and maximises foot contact area during late stance phase (Lavery et al, 1997). This kind of shoe induces a modification in the walking pattern and may cause pain in the muscles at the back of the lower leg as they begin to bear a greater load, but has been shown to significantly reduce the number of calluses when compared with retail footwear after 12 months' wear (Colagiuri et al, 1995). When designed with a point of the roll of the step placed immediately behind the metatarsal heads, such shoes reduce peak pressure by up to 30% (van Schie et al, 2000). A further reduction up to 20% is gained by the use of customised insoles (Uccioli, 2006).

Therapeutic footwear with insoles (e.g. microcellular rubber, polyurethane foam, moulded insoles) have been shown to reduce plantar pressures and ulcer recurrence when compared with retail shoes with leather board insoles (Viswanathan et al, 2004). Total-contact insoles can reduce pressure peaks by maximising the insole device–foot contact area (Foto and Birke, 1998), and custom-made, rather than flat, insoles have been shown to be more effective in offloading the first metatarsal head region (Bus et al, 2004).

Special care should be taken using insoles in retail shoes. If the shoe is not designed to accommodate the addition of an insole, the insertion of one will reduce the space available to the foot and increase friction. To avoid this, measure the depth of the foot at the level of the metatarsal heads, add the thickness of the insole to this measurement, and compare this figure with the inside depth of the shoe at the corresponding point. Ideally, the shoes should have soft, preferably heat-sensitive, uppers that enable comfortable accommodation of any foot deformities in addition to insoles.

The use of commercial available therapeutic, rather than custom-made, footwear offers a number of advantages, primarily the ease and speed of access (a stock can be kept in the clinic) and a reduction in cost per unit in comparison with custom-made products.

***Very high risk***

People with diabetes, neuropathy, foot deformity and a history of ulceration or amputation are at very high risk of ulceration (Lavery et al, 1998). People in this group experience a 50% rate of ulcer recurrence within 12 months of healing (Pound et al, 2005). Those at very high risk of ulceration are known to have abnormally elevated plantar pressures during walking, with the areas of peak pressure frequently occurring under the metatarsal heads and correlating with sites of callus and, ultimately, ulceration (Ledoux, 2008).

In contrast to the primary prevention of diabetic foot ulcers, various studies have demonstrated a protective role for footwear in secondary prevention, for both custom-made and prefabricated commercially available shoe models with the use of insoles. More than 20 years ago, Edmonds et al (1986) reported an ulcer relapse rate of 26% among those who wore custom-made therapeutic footwear, and 83% among those who wore retail shoes. The first author's own research (Uccioli et al, 1995) found similar relapse rates to be associated with therapeutic shoes with custom-made insoles (28%) versus retail footwear (58%).

In 2003, Busch and Chantelau assessed the efficacy of commercially available therapeutic shoes and insoles and found that 15% of people wearing this combination reulcerated 12 months after healing, while 60% in retail shoes reulcerated in the same period. Striesow (1998) tested commercially produced therapeutic shoes, according to Tovey's (1984) guidelines, and observed similar results.

Recommendations for the selection of footwear for this group are as outlined in the high-risk category, in particular footwear with rigid or rocker-bottom soles and moulded insoles. Multilayered, moulded insoles are preferable at this level of risk as they provide the greatest reduction in peak pressures (Foto and Birke, 1998; Mueller, 1999).

## Conclusion

Epidemiological surveys indicate that between 40% and 70% of lower-limb amputations worldwide are diabetes related, and around 85% of these are preceded by foot ulceration (International Diabetes Federation, 2005). Thus, the prevention of diabetic foot ulceration is a clinical priority.

Footwear plays a key role in diabetic foot ulcer risk. Indeed, unsuitable or ill-fitting footwear can insufficiently protect the insensate foot from trauma that may precipitate ulceration, or be itself the cause of trauma that progresses to ulceration. Conversely, correctly fitted therapeutic shoes and insoles may protect the at-risk foot from trauma and redistribute plantar pressures, thus protecting it against ulceration. Research suggests that the importance of footwear in diabetic foot ulcer prevention increases with the increasing level of ulcer risk experienced by the individual. However, prospective studies that have been carefully designed and carried out in large populations are needed to confirm the role of footwear in diabetic foot ulcer prevention.

It is important that clinicians are aware of the importance of giving footwear advice to all people with diabetes. Especially for those with neuropathy, the selection and use of suitable footwear may represent a valid means of diabetic foot ulcer prevention. ■

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