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# A Review of the Biomechanics of the Diabetic Foot

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*In general, diabetic foot ulcers result from abnormal mechanical loading of the foot, such as repetitive moderate pressure applied to the plantar aspect of the foot while walking. Diabetic peripheral neuropathy causes changes in foot structure, affecting foot function and subsequently leading to increased plantar foot pressure, which is a predictive risk factor for the development of diabetic foot ulceration. Prevention of diabetic foot ulceration is possible by early identification of the insensitive foot, therefore a foot "at risk," and by protecting the foot from abnormal biomechanical loading. Abnormal foot pressures can be reduced using several different approaches, including callus debridement, prescription of spe-*

*cial footwear, injection of liquid silicone, Achilles tendon lengthening, and so forth. Off-loading of the diabetic wound is a key factor in successful wound healing, as it is associated with reduced inflammatory and accelerated repair processes. Pressure relief can be achieved using various off-loading modalities including accommodative dressing, walking splints, ankle-foot orthosis, total contact cast, and removable and irremovable cast walkers.*

**Key words:** diabetic foot, foot ulcer, diabetic neuropathy, biomechanics

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**T**he diabetic foot remains one of the most serious complications of diabetes mellitus, with plantar ulceration a common complication of diabetic neuropathy. Ulcers commonly occur under the first, second, or third metatarsal head, and most neuropathic ulcers result from excessive and repetitive pressure applied to the foot while walking.<sup>1</sup> Several contributing factors lead to diabetic foot ulceration, such as peripheral neuropathy, foot trauma, foot deformity, increased foot pressures, and callus. Thus, foot ulcers develop as a consequence of a combination of intrinsic factors, such as reduced sensation, and extrinsic mechanical factors, such as high plantar pressures caused by abnormal mechanical loading of the foot. There is immense scope for the prevention of insensitive foot ulceration by identifying the "at-risk" foot. Prevention is extremely

important because the recurrence rate of foot ulcers is extremely high; foot ulceration can lead to amputation and is associated with increased mortality rate. This article will focus on the biomechanical changes in the foot that lead to diabetic foot ulceration.

The biomechanics of normal foot function will be discussed before the measurement of plantar pressure and changes in the foot caused by diabetes are considered. The biomechanics of diabetic foot ulcers will then be described. Finally, various methods for the biomechanical off-loading of diabetic foot ulcers will be discussed.

## NORMAL FOOT FUNCTION

One of the principal functions of the foot is its shock-absorbing capability during heel strike and its adaptation to the uneven surface of the ground during gait. In this function, the subtalar joint (allowing motion in 3 planes) plays a basic role. The ankle joint is the major point for controlling sagittal plane movements of the leg relative to the foot, which is essential for bipedal ambulation over flat or uneven terrain. The main motion of the first metatarsophalangeal joint and the lesser

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metatarsophalangeal joints is in the sagittal plane (dorsiflexion and plantarflexion).

The gait cycle consists of 2 basic components: the stance phase, during which the limb is in contact with the ground, and the swing phase, when the foot is in the air for limb advancement. The stance or weightbearing phase can be divided into 3 parts. The first is the contact phase, with the heel normally being the first area of the foot in contact with the ground. The midstance phase begins with opposite-side toe-off and full forefoot loading and terminates with heel lift. The third phase, the propulsion phase, can be further subdivided into 2 components: active propulsion and passive lift-off. Active propulsion begins with heel lift of the support side and ends with opposite-side heel strike. During this stage, the greatest horizontal and vertical forces are directed against the foot, and weightbearing is over a relatively small area in the forefoot. Therefore, the highest pressures are usually observed during this part of the stance phase. The passive lift-off begins with opposite heel contact and terminates with support-side toe-off.

Each part of the stance phase is characterized by a rocker action of the foot and ankle. During the contact phase, the heel (“heel rocker”) serves as an axis to allow smooth plantarflexion and to make full contact with the ground. During midstance, the ankle (“ankle rocker”) allows the tibia to advance forward over the foot, causing relative dorsiflexion of the ankle. This advances the center of pressure from the heel and midfoot to the forefoot. During active propulsion and passive lift-off, the first metatarsophalangeal joint (“forefoot rocker”) allows progression of the limb over the forefoot and accelerates heel lift. Thus, normal joint mobility in the joints of the foot is necessary to allow for normal foot function as described above.

During weightbearing activities, the plantar surface of the foot is exposed to ground reaction forces (GRFs), leading to tissue deformation. The relationship between force and deformation is expressed as the stress-strain relation. Stress, otherwise known as pressure, is equal to normalized force (force per unit area to which the force is applied). When a person is standing, the magnitude of the GRF is equal to body weight, with each foot experiencing about 50% of body weight distributed over the plantar surface area, which is predominantly a vertically directed force. During walking, the stresses applied to the feet are much higher than when standing for a number of reasons.<sup>2</sup> First, the amount of time that both feet are simultaneously in contact with the floor is substantially reduced during walking. Second, the rocker action as described above allows different parts of the foot to make contact with

the floor during different phases of the stance phase; thus, the plantar surface area changes in size and location while the GRFs progress from the heel to the hallux. Third, the GRFs vary in magnitude, with one peak during heel landing and a second peak during push-off with the forefoot. Therefore, the heel and the forefoot experience much higher peak pressures than does the midfoot.

Besides vertical GRFs, there are also GRFs in the horizontal direction causing a stress parallel to the foot skin. However, the magnitude of the anterior- or posterior-directed force is much smaller than the vertical-directed force and is, on average, about 25% of body weight compared to 120% to 150% of body weight for the vertical-directed force.

A minimum of 10 000 steps per day is considered to classify someone as an “active” individual, with less than 5000 steps per day indicating a “sedentary” lifestyle.<sup>3</sup> It is not difficult to see that with this number of steps, the foot is exposed regularly to the biomechanical stresses as described for each step.

## THE MEASUREMENT OF PRESSURE

Pressure is an estimated value and is calculated by dividing the measured force over the applied area. Force is thus directly measured, but the pressure value is calculated. Thus, the link between force and pressure is the area of force application. A force applied to a small area can do much more harm than the same force distributed over a larger area of the plantar surface.<sup>4</sup> Pressures are usually expressed in kilograms per square centimeter or in kilopascals ( $1 \text{ kg/cm}^2 = 98.1 \text{ kPa}$ ). The results of pressure measurements should be expressed as average pressure since the surface area of the transducer is usually known.<sup>5</sup>

Pressure measurement devices consist of a number of force sensor elements, but it is important to be aware of the variation in size of these elements. This difference in sensor sizes has major consequences for the calculation of pressure since a focal area of pressure under the foot will appear to have a lower value on a device with a larger element size. The clinical implication of this is that the results from different plantar pressure measurement devices are not always directly comparable, and as such, there is no universal threshold set for ulceration; thus, normal pressure ranges remain to be obtained for each different system. Normal pressure values for the whole foot have only been established for the optical pedobarograph<sup>6,7</sup> and the EMED platform.<sup>8</sup> A threshold of 700 kPa has been suggested for predicting foot ulceration using an EMED platform.<sup>9</sup> However, it might not be correct to use a single pressure threshold

for the whole foot. Regional norms seem to be a reasonable approach<sup>10</sup> since different areas experience different pressures and might have different thresholds. An early attempt to define borderline pressure values for the forefoot and toe region has been published by Kirsch et al.<sup>11</sup> Thus, whether there is one single threshold for damage to the foot or there are regional thresholds remains an unanswered question for now.

Almost all pressure measurement devices measure only vertical (or normal) pressure. It is believed by many authorities that shear stress may be an important etiological factor in the development of plantar ulcers.

Commercially available devices can be classified as platforms for measurement between the foot and the floor and as in-shoe systems to measure pressure between the foot and the shoe. Platform devices can be divided in footprint techniques and in computerized pressure measurement techniques.

Barefoot measurements of the foot-floor interface may demonstrate details of the effects of any foot deformity; however, a significant advantage of in-shoe measurements is that they can evaluate the effects of different types of footwear on pressure and pain relief. Thus, in-shoe measurements permit the actual assessment of the “unloading” effect of different types of insoles and footwear. Consequently, a major role of this type of measurement is for the appropriate prescription of footwear, braces, or orthoses.

A major advantage of in-shoe systems is that data can be collected for multiple steps without the problem of the subjects altering their gait to make contact with the platform. With in-shoe techniques, a more realistic approach of pressure measurement is possible, and the most important interface between the foot and the shoe can be assessed. Another advantage is that pressure can be measured during activities other than normal walking. It has been shown by Rozema et al<sup>12</sup> that normal walking is not always able to predict the plantar pressures experienced during other activities. Future in-shoe technique development will probably allow pressure measurement for a longer period of time so that pressure assessments can be done during real-life daily activities.

#### CHANGES IN THE FOOT CAUSED BY DIABETES AND PERIPHERAL NEUROPATHY

Diabetic peripheral neuropathy leads not only to reduced or loss of protective sensation but to changes in foot structure, as well as dryness of the skin, which can lead to excessive callus formation.<sup>13-15</sup> Changes in foot structure affect foot function can lead to high plantar foot pressure, which is an important predictive risk fac-

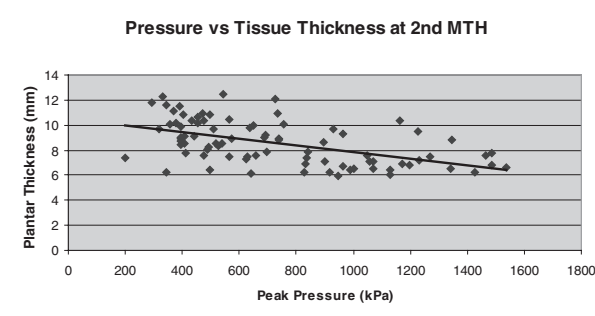


Fig. 1 Relation of plantar peak pressure and plantar tissue thickness at the second metatarsal head (MTH)  
Based on Abouaeha et al.<sup>22</sup>

tor for the development of diabetic foot ulceration.<sup>16,17</sup> It is important to note that foot ulcers also occur at pressures that are normal<sup>18</sup>; hence, this may be related to the lack of having a “pressure threshold” for developing foot ulceration, as mentioned earlier. High foot pressures usually occur at sites with bony prominence. Foot deformities, including bony prominences, have been shown to be predictive of increased plantar pressures and foot ulceration.<sup>15,19,20</sup> In addition, plantar tissue thickness is strongly associated with plantar pressure, indicating a close relation between the amount of cushioning (soft tissue) available and the pressure distribution at the forefoot.<sup>21,22</sup> Figure 1 illustrates this relation between peak pressure and tissue thickness at the second metatarsal head, indicating higher peak pressure at sites with reduced plantar tissue thickness.<sup>22</sup> Similarly, a strong relationship has been demonstrated between tissue thickness and history of ulceration in diabetic patients.<sup>23,24</sup> Qualitative changes of the plantar fat pad have also been observed in the form of a nonspecific fibrotic process beneath the metatarsal head in patients with diabetic neuropathy. This fibrotic tissue affects the intrinsic biomechanical properties of the plantar fat pad to act as a shock absorber and dissipate increased plantar pressures associated with neuropathy.<sup>25</sup>

Prominent metatarsal heads have traditionally been attributed to weakness of the intrinsic muscles of the foot, leading to toe deformities in patients with diabetic neuropathy. Fat cushions under metatarsal heads, which are imbedded in the flexor tendons, are believed to migrate distally with clawing and hammering of the toes, leaving the metatarsal heads relatively unprotected.<sup>26,27</sup> Evidence for atrophy of these muscles has been demonstrated as fatty infiltration in plantar muscles of diabetic patients with a history of foot ulceration.<sup>28</sup> However, more recent evidence has shown foot muscle atrophy in patients with diabetic neuropathy,

while there was no relationship between toe deformities and muscle atrophy, suggesting either that intrinsic muscle atrophy is not the primary causative factor or that loss of foot muscles precedes the development of toe deformities.<sup>29,30</sup> In a subsequent study, it was shown that diabetic neuropathic patients with a toe deformity have greater reduced submetatarsal head padding compared to patients without this deformity, indicating increased probability of high pressure and risk for foot ulcer development at these sites.<sup>31</sup>

Several authors have reported quantitative data of changes in the plantar tissue in the form of increased stiffness of the plantar tissue in diabetic patients with a history of ulcers, including Klaesner et al.<sup>32</sup> Increased hardness of the skin has been shown in diabetic patients with a history of foot ulceration<sup>33,34</sup> and has been associated with increased peak plantar foot pressures<sup>35</sup> and foot pressure distribution (a foot pressure parameter based on high-frequency power distribution).<sup>34</sup> Stress analysis based on finite element modeling of the foot confirmed that in foot models with reduced tissue thickness and increased skin hardness (such as observed in diabetic patients with neuropathy), normal and shear stresses at the foot sole were increased.<sup>36</sup> Similar results were obtained using magnetic resonance imaging scans to measure tissue deflection after application of an indentation load to the plantar skin. Increased stiffness was shown for diabetic plantar tissue, with higher shear and elastic moduli, indicating vulnerable tissue for ulceration.<sup>37</sup>

Charcot arthropathy usually causes gross deformation of the foot, thereby severely affecting functional use of the foot and causing abnormal pressure loading during walking. Peak plantar pressure in patients with Charcot arthropathy has been shown to be higher compared to patients with a neuropathic ulcer.<sup>38</sup> Patients with partially amputated feet were also shown to exhibit abnormal foot function and pressure loading,<sup>39</sup> and amputation of the hallux greatly increases pressure under the metatarsal heads.<sup>40,41</sup>

Callus areas have an effect on pressure loading and have been reported to be highly predictive of foot ulceration.<sup>42</sup> Callus acts as a foreign body, and its removal leads to lower plantar pressure in most cases.<sup>43,44</sup> Furthermore, neuropathic ulcers are commonly found beneath plantar calluses; therefore, frequent removal of callus is strongly recommended in diabetic patients.

Limited joint mobility of the foot and ankle has an effect on normal foot function and has therefore been suggested to increase plantar pressure in diabetic patients<sup>45,46</sup> and to be related to foot ulceration.<sup>47,48</sup> The etiology of limited joint mobility is unknown, although most evidence favors a relationship with the collagen

abnormalities and nonenzymatic glycation of soft tissue that occur in diabetes, resulting in thickening of skin, tendons, ligaments, and joint capsules, thereby reducing tissue flexibility.<sup>49,50</sup> Joint mobility of the subtalar joint was shown to be reduced in the ulcerated foot compared to the contralateral nonulcerated foot in diabetic neuropathic patients.<sup>47</sup> Similarly, ankle dorsiflexion and subtalar range of motion were reduced in diabetic patients with a history of plantar ulceration compared to patients without ulceration and nondiabetic controls.<sup>48</sup> In addition, ulceration of the great toe has been associated with a reduced range of motion at the first metatarsophalangeal joint.<sup>51</sup> However, it is also important to note that the relationship between limited joint mobility and foot ulceration has only been studied retrospectively. Thus, this relationship could also be interpreted as foot ulceration causing stiffening of the joints as opposed to limited joint mobility causing foot ulceration. Foot ulcers are frequently healed using casts for off-loading; in addition, patients are advised to minimize their levels of physical activity while healing the ulcer. It is quite likely that these 2 factors compromise and affect joint mobility. However, recent evidence in support of the limited joint mobility theory showed that the thickness of the plantar fascia of the foot was increased in diabetic patients both with and without neuropathy compared to nondiabetic controls.<sup>52</sup> In addition, an inverse correlation was shown between the thickness of the plantar tissue fascia and mobility of the metatarsophalangeal, indicating that soft tissue involvement may influence joint mobility, which may lead to increased loading of the foot.

Thus, foot deformity, including quantity and quality of plantar tissue, and limited joint mobility appear to be strong indicators of abnormal mechanical foot loading during walking, thereby causing high plantar foot pressures. Alleviation of these high-pressure areas is best achieved with accommodative footwear, including insoles and shoes. It is important to ensure that the altered foot shape is properly fitted and accommodated in the footwear. For many patients, normal high street footwear will not meet these criteria.

## BIOMECHANICAL ASPECTS OF FOOT ULCERATION

Foot ulcers in diabetes result from multiple pathophysiological mechanisms, including roles for peripheral neuropathy, peripheral vascular disease, foot deformity, increased foot pressures, and diabetes severity.<sup>53</sup> Trauma is needed, in addition to neuropathy and vascular disease, to cause tissue breakdown.

Trauma could be intrinsic, such as repetitive stress from high pressure and/or callus, or extrinsic, such as from ill-fitting footwear rubbing on the skin or an object inside the shoe (eg, drawing pin, pebble).

Ulcer sites are predominantly under the plantar surface of the toes, forefoot, and midfoot, followed by the dorsal surface of the toes and heel.<sup>15</sup> As plantar foot pressures are an important factor in the pathogenesis of diabetic foot ulceration, the proposed mechanism of pressure-induced ulcers is discussed next.

Skin is the mechanical link through which intrinsic forces are transmitted to the outside world and environmental forces to the skin and subcutaneous tissue. Ulceration seems to be caused by repetitive and/or excessive pressure on the surface of the insensitive skin, leading to tissue damage. If the same pressures occurred in a person with adequate sensation, the person would experience pain and avoid the offending pressures. However, in a person with loss of protective sensation, there is no warning of excessive pressures or tissue damage, and persistent localized pressures could lead to skin breakdown or ulceration. Foot deformities are usually responsible for these excessive pressures. In addition, healing of plantar ulcers is prevented as long as patients keep walking on their foot wounds, thus highlighting the key issue of mechanical off-loading.

Thus, excessive and/or repetitive pressures appear to be the main causative factor for development of skin breakdown. There are 3 mechanisms that account for the occurrence of these pressures: (1) increased duration of pressures, (2) increased magnitude of pressures, or (3) increased number of pressures.<sup>54</sup> The first mechanism includes relatively low pressures applied for a long period of time causing ischemia. Prolonged ischemia leads to cell death and wound formation, as has been demonstrated in a classic experiment.<sup>55</sup> An inverse relationship was shown between time and pressure and is shown in Figure 2. High pressures took a relatively short time to cause ulceration, while low pressures took a relatively long time. Thus, ulceration can develop at very low pressures but may take a few days to occur. This type of offending pressure and resulting ulcers can occur with ill-fitting footwear, improperly fitted orthotics, or prolonged resting of a heel on a bed or footrest.

The second mechanism of tissue injury includes high pressures acting for a short time period. This injury only happens if a large force is applied to a relatively small area of skin. This happens, for example, if a person steps on a nail or piece of glass, which is not unusual for diabetic neuropathic patients with reduced or loss of sensation. Alternatively, a "foot slap" may also

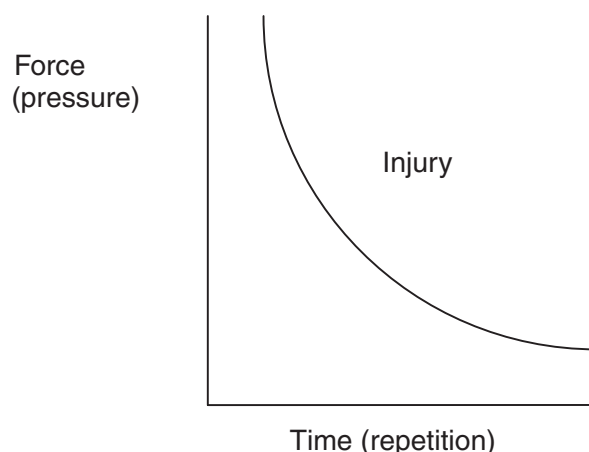


Fig. 2 Inverse relationship between force (pressure) and time (or repetition). As force (pressure) increases, the duration (time) or number (repetition) of force(s) required to cause tissue injury decreases. Based on Kosiak.<sup>55</sup>

conform to this mechanism. A foot slap indicates a reduced deceleration of the forefoot after heel strike caused by weak dorsiflexion muscles. It previously has been demonstrated that high rates of tissue deformation lead to cellular death, while comparable gradually applied loads do not.<sup>56</sup> It is therefore suggested that control of the velocity of the forefoot descending after heel strike by using ankle foot orthosis could possibly help in prevention of diabetic foot ulcers. The third mechanism of injury comes from repetitions of pressure, which in engineering terms would lead to an equivalent syndrome of mechanical fatigue. Mechanical fatigue is defined as failure of a structure or biological tissue at a submaximal level to maintain integrity because of repeated bouts of loading. This type of injury seems to occur in the insensitive skin and subcutaneous tissue of the neuropathic foot.

The body will respond to repeated high pressures or micro-trauma with callus formation to protect the skin from further damage. However, if callus formation becomes excessive, it will contribute to higher pressure and should therefore be removed at a regular interval.<sup>43,44</sup>

Although a high level of activity has traditionally been regarded as "repetitive stress" and therefore considered as a risk factor for diabetic foot ulceration, interesting new evidence has shown that patients who were less active were more likely to develop foot ulceration.<sup>57,58</sup> In addition, the risk may not be related to the level of activity but the increased variability in physical activity, which was recently reported to be associated with the development of foot ulceration.<sup>59</sup>

In addition to the different types of mechanisms of excessive pressure loading, abnormal alignment of the foot also affects pressure loading on the foot. Feet with “abnormal” alignment of the forefoot or rearfoot exhibit a different loading pattern than do normally aligned feet. Both nondiabetic and diabetic planus feet (everted rearfoot, inverted forefoot, and low arch) have been shown to experience greater peak pressures than do nondiabetic rectus feet (a neutral rearfoot and forefoot with normal arch morphology).<sup>60</sup> This is in agreement with previous reports of an association between type of foot deformity and callus and ulcer location in a group of diabetic patients with active ulceration.<sup>61</sup> In this particular report, 88% (15/17) of patients with an uncompensated forefoot varus or forefoot valgus (inverted or everted forefoot) had ulcers located at the first or fifth metatarsal head. Similarly, an inverted heel position has been associated with lateral ulcers, whereas an everted heel position has been associated with medial ulcers.<sup>62</sup>

Thus, not only the magnitude of the plantar pressure is important in causing foot ulceration, but several other factors such as the rate of increase of pressure, duration of high pressure, and the frequency of applied pressure to the skin should be taken into account. Abnormal pressures may not just be caused by the effects of diabetes, and it seems reasonable to hypothesize that diabetic patients with foot type characteristics that differ from the norm are more likely to develop high foot pressures and ulceration than are diabetic patients with normal foot morphology.

**BIOMECHANICAL INTERVENTIONS TO OFF-LOAD THE FOOT**

Preventive care to reduce foot pressures and thereby the incidence of foot ulceration includes callus debridement as well as provision of pressure-reducing insoles and therapeutic footwear. Appropriate management of callus is crucial in diabetic patients. Callus needs to be removed frequently as it can build up quickly, with some patients needing debridement as often as every 3 to 4 weeks or sometimes even more frequently.<sup>44</sup> Traditionally, callus is removed when excessively formed under the diabetic foot; however, only a few preliminary studies have addressed how callus buildup can be minimized.

A small randomized placebo-controlled trial showed a reduction in callus grade in patients wearing rigid orthotic in-shoe devices compared to conventional podiatric care.<sup>63</sup> Similarly, wearing microcellular rubber insoles footwear for 6 months was shown to reduce hardness of the plantar tissue and

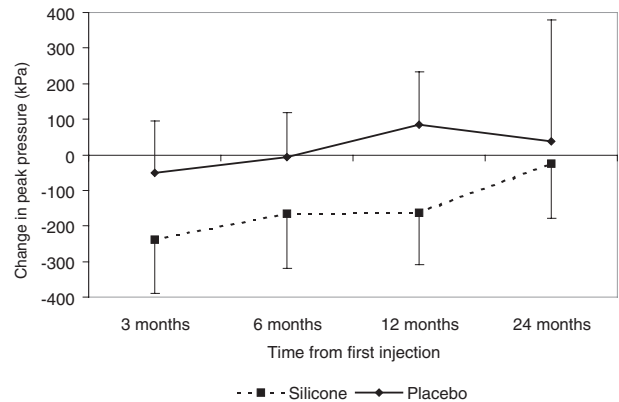


Fig. 3 The mean change in peak plantar pressure (kPa) from baseline at 3, 6, 12, and 24 months after injection with liquid silicone and saline (placebo). Error bars are 95% confidence intervals. Based on van Schie et al.<sup>67</sup>

foot pressure distribution in diabetic neuropathic patients.<sup>34</sup>

The injection of collagen under callus in diabetic patients with previous neuropathic ulceration was shown to reduce the surface area of callus compared to a nontreated control group at 8 months postinjection.<sup>64</sup>

The therapeutic use of liquid silicone injections in the foot has been suggested to improve cushioning at callus sites, corns, and localized painful areas.<sup>65</sup> In a randomized placebo-controlled trial with diabetic neuropathic patients, it was shown that injected liquid silicone decreased peak plantar pressure and callus formation and increased plantar tissue thickness under silicone-treated areas.<sup>66</sup> This cushioning effect was still significant at 1 year following the injections, although at 2-year follow-up, the cushioning properties appeared to be reduced, suggesting that booster injections may be required in certain patients<sup>67</sup> (Figs. 3 and 4). The magnitude of change was greater at injection sites with a lower baseline thickness and a higher baseline peak pressure.<sup>68</sup> No side effects were reported in the trial; in addition, there is a large body of anecdotal evidence to support the safety of this procedure.<sup>65</sup> Thus, a few different treatments to reduce foot pressures and the risk of foot ulceration have been developed. However, whether the injection of liquid silicone can actually prevent foot ulceration needs to be confirmed in larger trials.

Different surgical methods have been suggested and used for reduction of foot pressures and prevention of ulceration. Metatarsal head resection is a surgical technique that can be used to accelerate wound healing under a metatarsal head area, usually greatly exposed to

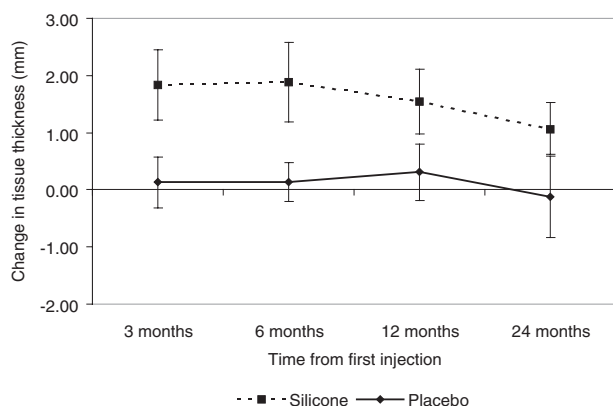


Fig. 4 The mean change in plantar tissue thickness (mm) from baseline at 3, 6, 12, and 24 months after injection with liquid silicone and saline (placebo). Error bars are 95% confidence intervals. Based on van Schie et al.<sup>67</sup>

high pressure. Although pressure reduction was evident in a series of 16 cases at 6 to 8 weeks following surgery, it is not known whether this procedure may result in a transfer of peak pressure to other areas in the foot in the long term.<sup>69</sup> However, in 2 different series, no recurrent ulcers or transfer lesions were seen during follow-up periods of 6 to 20 months and  $14 \pm 11$  months.<sup>69,70</sup>

Dorsiflexion metatarsal osteotomy has been suggested as an alternative to metatarsal head resection, as this procedure does not violate the metatarsophalangeal joint.<sup>71</sup> It elevates prominent metatarsal heads, thereby balancing the metatarsal heads and redistributing weightbearing forces more evenly across the forefoot, although no pressure data are available to confirm this theory. First metatarsophalangeal joint arthroplasty increases the range of motion at the articulation of the hallux to the first metatarsal and is a technique commonly used to improve healing of ulcers at the hallux. From a 6-month retrospective analysis, this procedure was reported to result in a faster healing rate of ulcers and in fewer recurrent ulcers compared to conservative (nonsurgical) treatment.<sup>72</sup>

Achilles tendon lengthening (ATL) has been shown to increase dorsiflexion range of motion, decrease forefoot plantar pressure, and reduce the rate of ulcer recurrence in patients with diabetic forefoot ulcers.<sup>73-75</sup> The increase in dorsiflexion range of motion was originally thought to lead to subsequent reduction in forefoot pressure. However, in a recent report, plantar pressures were shown to be initially reduced but were, however, back at preprocedure levels at 8-month follow-up, whereas dorsiflexion range of motion had remained increased.<sup>76</sup> From the results of a comprehensive gait

analysis, the authors concluded that the initial decrease in forefoot pressure appeared to be caused by a reduced plantarflexion power during gait rather than increased range of motion.<sup>76</sup> This procedure did not result in a measurable change in functional limitations, although patients who received ATL and a total contact cast (TCC) reported lower physical functioning 8 months following the procedure compared to patients who received a TCC only, suggesting that additional physical therapy may be required in patients receiving ATL.<sup>77</sup> Results from a different series indicated that the most important complication of ATL is the development of a transfer lesion to the heel.<sup>78</sup> Although there are risks with every surgical procedure, it is generally accepted that the benefits of the ATL procedure outweigh the risk for patients with recurrent ulcers and limited dorsiflexion at the ankle joint.<sup>77</sup>

## OFF-LOADING DEVICES FOR FOOT ULCERS

Off-loading of the diabetic wound is a key factor in successful wound healing. Several devices have been described in the literature, most of them effective in off-loading and healing wounds.

The TCC is generally viewed as the reference standard for off-loading the diabetic wound; however, several useful alternatives exist.<sup>79</sup> Although the TCC is probably the most effective in off-loading the wound, the problem with this method is that regular checking of the wound is difficult, as this means making a new cast after every check. However, new data have demonstrated the successful use of a nonremovable fiberglass cast with a treatment window at the ulcer site, allowing daily inspection of the wound.<sup>80,81</sup> The use of a TCC is contraindicated in acutely infected or ischemic feet. Nonetheless, ulcers with moderate ischemia or infection were shown to be effectively treated using a TCC.<sup>82</sup> However, when peripheral arterial disease and infection are both present or in case of heel ulcers, alternative off-loading methods are required as the outcome was poor in these cases.<sup>82</sup> Other devices, such as removable walkers, Scotchcast boot, half shoes, healing shoes, accommodative dressing, and so forth, are equally or not as effective in off-loading; however, their main advantage is that regular inspection of the wound is possible. Obviously, this may at the same time be the main disadvantage, as the possibility of removing the device makes it very easy for patients not to conform with the off-loading treatment.

The Scotchcast boot is a well-padded plaster boot cut away by the ankle and made removable by cutting the cast over the dorsum of the foot. Windows are cut under the ulcer, and the boot is worn with a cast sandal

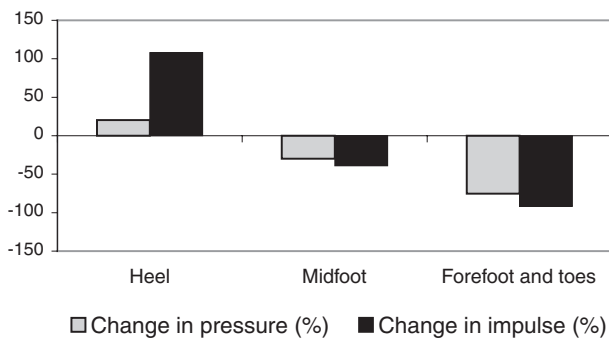


Fig. 5 Change in mean peak plantar pressure and impulse (pressure-time integral) in the total contact cast as compared with the shoe condition (cast shoe with a flat 0.5-in PPT compliant insole). Based on Shaw et al.<sup>86</sup>

to increase patients' mobility while the cast protects the ulcer from any excessive pressure.<sup>83,84</sup> In a retrospective analysis, it was observed that healing rates were comparable to using the half shoe.<sup>85</sup>

The TCC is a well-molded, minimally padded cast, which maintains contact with the entire plantar aspect of the foot and lower leg. A large proportion of the pressure reduction achieved in the forefoot of the TCC has shown to be transmitted along the cast wall or to the rearfoot<sup>86</sup> (Fig. 5). The advantage of the contact cast over other off-loading methods is that it is highly effective in reducing pressure, immobilizing tissues, and reducing edema, and it is not removable by the patient. However, the cast can create secondary lesions and limits the use of special dressings or topical agents. In addition, it requires a lot of expertise and time for application compared to other modalities. It is therefore not always a practical option in some clinics and for certain patients. The use of fiberglass materials with variable rigidity to make a TCC was shown to reduce some of the classic side effects seen with the traditional TCC, as reduced skin lesions and improved patient acceptability were reported.<sup>80</sup>

Although DH Pressure Relief Walkers and Aircast pneumatic walkers (both removable walking casts) were shown to be as effective in reducing foot pressures as the TCC,<sup>87,88</sup> a randomized clinical trial showed that TCC healed a higher proportion of wounds in a shorter time compared to a removable cast walker.<sup>89</sup> In contrast, in another trial, there was no difference in healing rates between using alternative off-loading methods such as accommodative dressing, a healing shoe, and a walking splint compared to using a TCC when controlling for ulcer grade and width.<sup>90</sup> Off-loading method was selected on the basis of ulcer loca-

tion, patient age, and duration of ulceration, and treatment was not randomized. The results showed that TCC was more frequently used for ulcers at the metatarsal area and in younger patients with ulcers of longer duration.<sup>90</sup>

Recently, fascinating results have presented the explanation for the importance of off-loading in wound healing. It was demonstrated that pressure relief with a TCC was associated with changes in the histology of neuropathic foot ulcers, indicating reduced inflammatory and accelerated repair processes.<sup>91</sup>

It has also been suggested that the effectiveness of an off-loading device to heal foot ulcers depends completely on whether the device is worn during all weightbearing activities. In a small study, it was noted that patients wore their removable cast walkers for only 28% of their total daily activities, indicating that this may explain poor healing rates in certain trials.<sup>92</sup> These results have led to the development of the instant TCC, which is a removable cast walker wrapped with cohesive bandage or plaster of Paris, making it "irremovable." Recent evidence from preliminary studies on the effectiveness of an irremovable TCC (iTCC) showed that the iTCC and TCC resulted in equal healing times, while a second study reported faster healing in an iTCC compared to a removable cast walker.<sup>93,94</sup> Even though this promising technique is suggested to address many of the disadvantages of the TCC, it does not change the fact that this type of device is not suitable for all patients and that in addition to off-loading, wound healing needs debridement, treatment of infection, and, in some cases, revascularization.

The ankle-foot orthosis has been suggested to be a useful alternative to casting techniques to off-load the diabetic foot during wound healing and to prevent ulceration.<sup>95</sup> It is proposed that an ankle-foot orthosis prevents high-velocity impact between the ground and the plantar surface of the foot, thereby controlling the rate of mechanical loading of the tissues. In fact, most casting techniques indirectly reduce rate of loading of the forefoot by immobilizing the ankle joint. There is only limited evidence of the efficacy of ankle-foot orthosis in ulcer healing and prevention; however, preliminary evidence indicates pressure reductions at ulcer sites ranging from 70% to 92% and significantly reduced loading rates.<sup>95</sup>

Thus, several off-loading modalities have been described to prevent (re)ulceration and to improve wound healing. Although the TCC appears to be the reference off-loading method, other devices have also shown to be effective in wound healing. The choice of off-loading depends on the patient and clinical situation, and therefore more future clinical trials compar-

ing different off-loading methods (ie, randomized controlled trials) will help to improve future clinical decision making in the prevention and treatment of diabetic foot ulcers.

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