Foot deformity in diabetic neuropathy. A radiobiological and biomechanical analysis

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Chapter 7

Elevated plantar pressures in neuropathic diabetic patients with claw/hammer toe deformity

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Chapter 7

Abstract

Elevated plantar foot pressures during gait in diabetic patients with neuropathy have been suggested to result, among other factors, from the distal displacement of sub-metatarsal head (MTH) fat-pad cushions caused by claw/hammer toe deformity. The purpose of this study was to quantitatively assess these associations.

Thirteen neuropathic diabetic subjects with claw/hammer toe deformity, and 13 age- and gender-matched neuropathic diabetic controls without deformity, were examined. Dynamic barefoot plantar pressures were measured with an EMED pressure platform. Peak pressure and force-time integral for each of 11 foot regions were calculated. Degree of toe deformity and the ratio of sub-MTH to sub-phalangeal fat-pad thickness (indicating fat-pad displacement) were measured from sagittal plane magnetic resonance images of the foot.

Peak pressures at the MTHs were significantly higher in the patients with toe deformity (mean 626 [SD 260] kPa) when compared with controls (mean 363 [SD 115] kPa, \( P < 0.005 \)). MTH peak pressure was significantly correlated with degree of toe deformity (\( r = -0.74 \)) and with fat-pad displacement (\( r = -0.71 \)) (\( P < 0.001 \)). The ratio of force-time integral in the toes and in the MTHs (toe-loading index) was significantly lower in the group with deformity.

These results show that claw/hammer toe deformity is associated with a distal-to-proximal transfer of load in the forefoot and elevated plantar pressures at the MTHs in neuropathic diabetic patients. Distal displacement of the plantar fat pad is suggested to be the underlying mechanism in this association. These conditions increase the risk for plantar ulceration in these patients.
Introduction

It has been well documented that the mechanical pressures applied to the plantar surface of the foot during gait are elevated in patients with diabetes mellitus and peripheral neuropathy. These excessive pressures in feet that lack protective sensation are a major risk factor for plantar ulceration, which is the most common precursor to lower-extremity amputation among persons with diabetes. Foot deformity is an important factor explaining why plantar pressures are increased in neuropathic feet: prominent metatarsal heads (MTHs), callus formation, limited joint mobility, Charcot deformity, and partial foot amputation have all been associated with increased levels of plantar pressure.

For many years, clawing or hammering of the toes, which is a common deformity in the diabetic population, has been another factor suggested to cause elevated plantar pressures in the forefoot. The mechanism behind this relationship would be that hyperextension of the metatarsal-phalangeal (MTP) joint, characteristic of claw/hammer toe deformity, causes the protective and shock-absorbent sub-MTH fat-pad cushions to displace distally in the foot, exposing the MTHs to more focal and increased dynamic plantar pressures.

Surprisingly, quantitative evaluations of these associations are scant in the literature. Recently, Mueller et al. showed that the degree of MTP joint extension was significantly correlated with MTH plantar pressure in the diabetic neuropathic foot. Masson et al. found half of their studied diabetic patients with claw toe deformity to have abnormally high plantar pressures. However, both these studies did not identify the mechanism by which toe deformity was related to increased pressure levels. Abouesha et al. found sub-MTH tissue thickness to be significantly inversely correlated to peak pressure at the central MTHs in neuropathic diabetic patients, but did not report on the role that toe deformity may have played in this association.

With the use of magnetic resonance imaging (MRI), we recently provided evidence for the presence of distal fat-pad displacement in neuropathic feet with claw/hammer toe deformity and suggested that, as a result, plantar pressures in these feet are elevated. (chapter 5) Therefore, the purpose of this study was to compare plantar foot pressures between neuropathic diabetic patients with claw/hammer toe deformity and similar patients without deformity and to determine the underlying mechanism in a possible association between toe deformity and elevated plantar pressure. We hypothesized that plantar pressures at the MTHs are significantly higher in neuropathic subjects with toe deformity when compared with subjects without deformity and that changes in plantar fat-pad geometry play a contributing role in these differences.
Chapter 7

Methods

Subjects

Thirteen diabetic subjects (eight men, five women) with distal symmetric sensory neuropathy and MTP joint hyperextension deformity (experimental group) and 13 age- and gender-matched diabetic subjects with neuropathy and normally aligned toes (control group) were examined. Subjects in the experimental group were selected based on deformity present in the second or third ray of the foot while non-weight bearing. The presence of deformity was assessed subjectively and confirmed by MRI evaluation as described below. One foot of each subject was selected for data collection. This foot was randomly assigned if not excluded by the criteria mentioned below. The presence of neuropathy was confirmed by the inability to feel the pressure of a 10-grams monofilament at one or more of six plantar foot sites and by an abnormal vibration perception threshold measured according to standard methods on the dorsal surface of the hallux using a Biothesiometer (Bio-Medical Instrument Company, Newbury, OH). Baseline subject characteristics are summarized in Table 1.

Table 1. Baseline patient characteristics.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Experimental group (n = 13)</th>
<th>Control group (n = 13)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>56.3 (8.6)</td>
<td>57.2 (5.5)</td>
</tr>
<tr>
<td>Height (m)</td>
<td>1.77 (0.10)</td>
<td>1.74 (0.06)</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>85.5 (14.6)</td>
<td>79.5 (10.3)</td>
</tr>
<tr>
<td>Body mass index (kg/m^2)</td>
<td>27.2 (2.9)</td>
<td>26.4 (4.1)</td>
</tr>
<tr>
<td>Diabetes duration (years)</td>
<td>32.8 (12.0)</td>
<td>31.1 (12.8)</td>
</tr>
<tr>
<td>HbA1c (%)</td>
<td>7.8 (1.1)</td>
<td>6.0 (0.9)</td>
</tr>
<tr>
<td>History of ulceration (n)</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Neuropathy duration (years)*</td>
<td>12.4 (5.3)</td>
<td>11.6 (7.6)</td>
</tr>
<tr>
<td>Vibration perception threshold (Volts)</td>
<td>33.5 (12.2)</td>
<td>36.2 (10.6)</td>
</tr>
<tr>
<td>Foot studied (L/R)</td>
<td>6/7</td>
<td>6/7</td>
</tr>
<tr>
<td>Selected toe (2/3)</td>
<td>9/4</td>
<td>9/4</td>
</tr>
<tr>
<td>Toe angle (degrees)</td>
<td>-24.7 (9.7)</td>
<td>-1.8 (6.6)</td>
</tr>
</tbody>
</table>

Data are means (SD) or numbers (n). *As derived from medical records or, when absent, estimated by the patient based on the first appearance of neuropathic symptoms. None of the previous ulcers were located in the MTH region.

\* P < 0.001 vs. Experimental group.
Elevated plantar pressures in claw/hammer toe deformity

The exclusion criteria were: 1) foot deformities other than claw/hammer toes that affect MTH plantar pressure: limited joint mobility, lower-extremity amputation, and Charcot neuro-osteoarthropathy. Absence of limited joint mobility was indicated by a lack of significant resistance while moving the hallux through a full range of MTP joint extension and flexion. The absence of Charcot arthropathy was confirmed by MRI evaluation; 2) significant peripheral vascular disease defined by absent dorsalis pedis or tibialis posterior arterial pulses combined with an ankle-brachial systolic blood pressure index <0.75 or toe pressures <50 mmHg; 3) age <40 and >65 years; 4) neuropathic syndromes other than distal symmetric neuropathy associated with diabetes; 5) significant musculo-skeletal problems in the lower extremities, including injury, fracture, and previous surgery; 6) rheumatoid arthritis; 7) current ulceration in either foot or edema in the examined foot; 8) inability to walk unaided; and 9) conditions precluding MRI. All subjects signed a written informed consent form prior to participation in the study, which was approved by the medical ethics committee of the Academic Medical Center of the University of Amsterdam.

Procedures

Dynamic barefoot plantar pressures were measured using an EMED-NT pressure platform (Novel, Munchen, Germany) which consists of capacitance-based sensors in a spatial resolution of two sensors per cm² that were sampled at 70 Hz. Five trials at the subjects' own pace using a 'two-step' gait approach to the platform (chapter 6) were collected. Abundant amounts of callus were removed from the foot just prior to data collection. Subjects were instructed to walk across the platform in a normal manner. Trials in which the subject did not hit the platform with the entire foot, targeted for the platform, or substantially altered gait or speed, as judged by the investigator, were not saved for analysis. The pressure data was analyzed with Novel-Ortho and Novel-Win software. Automated masking divided the foot into 11 anatomically referenced regions: a heel, midfoot, five MTH regions, and four toe regions (Figure 1, see Appendix, p. 181). For each region, peak pressure, pressure-time integral, normalized force-time integral, and contact area was calculated and the average from the five walking trials was used for further analysis. Pressure-time integral of a region is defined as the integral of pressure over time measured in the single sensor within that region showing the peak pressure. Force-time integral of a region is defined as the integral of force over time measured in all sensors within that region. The main variables of interest were peak pressure and pressure-time integral at the MTHs and toe regions of the selected ray of interest (second or third ray). A 'toe-loading' index was calculated, similar to previously described methods, and defined by the ratio of force-time integral in the lesser toes and in the lesser MTH regions (second to fifth ray). This index was used to determine the relative use of toes and MTHs for propulsion during stance. Due to the 'cocked-up' position of the toes when they are clawed
or hammered, we expected less contact with the ground during propulsion in the experimental group. Therefore, contact area at the lesser toe regions was also a variable of interest.

Details of MRI data collection are reported elsewhere.\(^{13,22}\) \((\text{chapter 5})\) In short, at 1.5 Tesla, high-resolution (512x512 pixels) T1-weighted sagittal plane spin-echo images of the foot were acquired between the first and fifth MTHs with the subject non-weight bearing (see Figure 2 for two example images, Appendix, p. 182). From these images, the degree of toe deformity was measured and defined by the angle between a line parallel to the sole of the forefoot and the bisector of the proximal phalanx. This angle was named the ‘toe angle’ with a negative value denoting extension (dorsiflexion). All subjects in the experimental group had a toe-extension angle more than two standard deviations larger than the average toe angle in the control group (i.e., >13 degrees). The MR images were also used to measure fat-pad thickness plantar to the MTH (sub-MTH) and the proximal phalanx (sub-phalangeal), both at three proximal-to-distal locations.\(^{13}\) \((\text{chapter 5})\) The average outcome of the three measures per site was used for further analysis. The ratio of sub-MTH to sub-phalangeal fat-pad thickness (named ‘thickness ratio’) was used to indicate fat-pad displacement. Comparisons between the neuropathic subject groups for these dependent variables are reported in detail in a companion study.\(^{13}\) \((\text{chapter 5})\) Here, we suffice with reporting the values for sub-MTH fat-pad thickness and thickness ratio for the 13 cases per group and focus mainly on the association between these measures of fat-pad geometry and barefoot plantar pressure.

Although several subjects had more than one deformed toe in the examined foot, only one was chosen for statistical analysis because of the expected dependence of plantar pressures across the individual MTH regions. The second toe was chosen unless this toe was not deformed, in which case the third toe was included (Table 1). All statistical analyses were performed using SPSS (SPSS, Chicago, IL). For all dependent variables, the data were normally distributed. Independent t-tests assessed for statistical significance between the two subject groups. Pearson's correlation coefficients were calculated between selected variables of interest in the pooled group of 26 neuropathic subjects. A significance level of \(P < 0.05\) was used for all analyses.

**Results**

At the selected MTH region (second or third ray), peak pressure was 1.7 times higher in the experimental group when compared with the control group \((P < 0.005, \text{Table 2})\). Similarly, pressure-time integral was a same order of magnitude higher in the subjects with toe
Elevated plantar pressures in claw/hammer toe deformity

deformity ($P < 0.005$). Figure 2 (see Appendix, p. 182) shows an example of the comparison of pressures in two matched subjects. In 11 of 13 subjects with deformity, peak pressure and pressure-time integral at the selected MTH region were significantly higher than in their matched controls. At the selected toe region (second or third toe), peak pressure and pressure-time integral were lower in the experimental group but these differences were not significant ($P > 0.1$).

| Table 2. Plantar pressure and plantar fat-pad geometry data. |
|------------------|------------------|
| Variable         | Experimental group (n = 13) | Control group (n = 13) |
| Peak pressure (kPa) |                      |                      |
| Selected MTH     | 621 (252)           | 363 (115)<sup>a</sup>|
| Selected toe region | 108 (72)           | 144 (76)            |
| Pressure-time integral (kPa·s) |                    |                      |
| Selected MTH     | 235.7 (111.2)       | 129.9 (38.5)<sup>b</sup>|
| Selected toe region | 33.6 (25.4)        | 38.0 (25.2)         |
| Force-time integral (N·s/kg)<sup>*</sup> |                |                      |
| Lesser MTHs (2-5) | 3.05 (0.51)         | 2.66 (0.68)         |
| Lesser toes (2-5) | 0.12 (0.06)         | 0.18 (0.08)<sup>a</sup>|
| Toe loading index | 0.038 (0.019)       | 0.072 (0.030)<sup>b</sup>|
| Contact area lesser toes (cm<sup>2</sup>) | 8.2 (1.9)          | 12.1 (1.5)<sup>c</sup>|
| Sub-MTH fat-pad thickness (mm) | 2.4 (1.4)         | 6.4 (1.5)<sup>c</sup>|
| Thickness ratio   | 0.27 (0.15)         | 0.81 (0.13)<sup>c</sup>|

Data are means (SD). *Force-time integrals are normalized with respect to body weight.

<sup>a</sup>$P < 0.05$, <sup>b</sup>$P < 0.005$, <sup>c</sup>$P < 0.001$ vs. Experimental group.

A comparison of peak pressure and pressure-time integral values between the groups for all 11 anatomical regions in the foot showed significantly higher values in the experimental group for the central MTHs (MTH 2-4) only; in the other regions of the foot no significant differences between the groups were found. The highest peak pressure in the foot was present within the central MTHs in nine experimental subjects, compared with only two controls.

Contact area for all individual toe regions and all lesser toes grouped was significantly smaller in the experimental group when compared with controls (Table 2, $P < 0.001$). No significant differences in contact area were present in the other foot regions.
In all lesser toes grouped, force-time integral was significantly lower in the experimental group \( (P < 0.05) \). Force-time integral in the lesser MTHs was 15% larger in the experimental group than in the control group, but this difference was not significant \( (P = 0.1) \). The toe-loading index was significantly lower in the experimental group \( (P < 0.005) \).

Sub-MTH fat pads were significantly thinner and thickness ratio was significantly smaller in the experimental group when compared with controls \( (P < 0.001, \text{Table 2}) \), indicating fat-pad displacement, as was reported in detail elsewhere.\(^{13} \text{(chapter 5)} \) MTH peak pressure was significantly inversely correlated with toe angle \( (r = -0.74, P < 0.001, \text{Figure 3A}) \). Thus, more deformity was associated with higher peak pressures. Additionally, sub-MTH fat-pad thickness \( (r = -0.71) \) and thickness ratio \( (r = -0.71) \) were also significantly correlated with MTH peak pressure \( (P < 0.001, \text{Figures 3B and 3C}) \).

<table>
<thead>
<tr>
<th>Toe angle (degrees)</th>
<th>1200</th>
<th>1000</th>
<th>800</th>
<th>600</th>
<th>400</th>
<th>200</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>MTH Peak pressure (kPa)</td>
<td>-50</td>
<td>-40</td>
<td>-30</td>
<td>-20</td>
<td>-10</td>
<td>-5</td>
<td>0</td>
</tr>
<tr>
<td>( R^2 = 0.54 )</td>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sub-MTH fat-pad thickness (mm)</th>
<th>1200</th>
<th>1000</th>
<th>800</th>
<th>600</th>
<th>400</th>
<th>200</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>MTH Peak pressure (kPa)</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
</tr>
<tr>
<td>( R^2 = 0.50 )</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Thickness ratio</th>
<th>0.0</th>
<th>0.2</th>
<th>0.4</th>
<th>0.6</th>
<th>0.8</th>
<th>1.0</th>
<th>1.2</th>
</tr>
</thead>
<tbody>
<tr>
<td>MTH Peak pressure (kPa)</td>
<td>1200</td>
<td>1000</td>
<td>800</td>
<td>600</td>
<td>400</td>
<td>200</td>
<td>0</td>
</tr>
<tr>
<td>( R^2 = 0.50 )</td>
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</tbody>
</table>

Figure 3. Scatter plots for the association between MTH peak pressure and (A) toe angle, (B) sub-MTH fat-pad thickness, and (C) thickness ratio for the experimental (closed squares) and control (closed triangles) groups. Linear regression lines and \( R^2 \) values are provided for the pooled data of 26 subjects.

Discussion

The results clearly show that claw/hammer toe deformity is associated with significantly higher peak pressure and pressure-time integral at the MTHs in the neuropathic feet studied. Peak pressure was 1.7 times and pressure-time integral was 1.8 times higher in the subjects with deformity when compared with subjects without deformity. The degree of toe deformity (toe angle) explained 54% of the variance in peak pressure at this site, which
Elevated plantar pressures in claw/hammer toe deformity

demonstrates that toe deformity is a strong contributor to elevated plantar pressure in this group of subjects.

The present findings confirm recent reports from Mueller et al.\textsuperscript{26}, who found a significant association between MTP joint angle and MTH peak pressure in a group of 20 neuropathic diabetic patients, and Abouaesha et al.\textsuperscript{2}, who found a significant inverse correlation between sub-MTH soft-tissue thickness and peak pressure in 157 neuropathic diabetic patients. Additionally, Ahroni et al.\textsuperscript{3}, in a large cohort of 517 diabetic patients, showed those with claw/hammer toe deformity or prominent MTHs to have significantly higher MTH peak pressures measured inside the shoe than those without. The present results extend these reported findings by showing a significant association between thickness ratio, as indicator for fat-pad displacement, and MTH peak pressures ($r = -0.71$). Based on this finding, and earlier findings in the same subject sample that toe deformity is strongly associated with fat-pad displacement.\textsuperscript{13} (chapter 5), we suggest that the primary factor in explaining the association between claw/hammer toe deformity and elevated plantar pressure is the distal displacement of fat-pad cushions causing reduced fat-pad thickness underneath the MTHs.

The clinical importance of studying the biomechanics of claw/hammer toe deformity in neuropathic diabetic patients has been demonstrated by several prospective population-based studies which showed that this structural abnormality is a significant independent predictor of plantar ulceration in these subjects.\textsuperscript{11} Moreover, Lavery et al.\textsuperscript{21} found that 78% of patients with plantar forefoot ulcers had a rigid forefoot deformity, which included claw/hammer toes, that was directly associated with the site of ulceration. The present findings illustrate the mechanism by which toe deformity and ulceration may be related and suggest that neuropathic subjects with deformity are at increased risk for ulcer development, even though a threshold of barefoot plantar pressure above which ulceration occurs has not been clearly identified.\textsuperscript{6}\textsuperscript{,}21 The first MTH and hallux are the most common sites for abnormally high pressures and plantar ulcers to occur in the neuropathic foot.\textsuperscript{4} In the present study, the second and third MTHs were the most common sites for the highest peak pressure, which provides further support for the clinical significance of lesser toe deformity in these patients.

The reported correlation coefficients between structural forefoot abnormalities and MTH plantar pressure vary from 0.42 to 0.62.\textsuperscript{2,3,26,34} Moreover, multiple factor regression analyses reveal that up to about 50% of the variance in MTH peak pressure in the diabetic neuropathic foot can be explained.\textsuperscript{26,34} The correlation values in the present study varied from -0.71 to -0.74 with $R^2$ values of 50-54%. To date, these are the highest numbers reported for single predictors of peak pressure. Still, about half of the variance in peak
pressure remains unexplained and several factors may be related to this outcome. Soft-tissue properties, such as stiffness, have been shown to be altered in diabetic feet\textsuperscript{20}; less compliant tissue transmits more load to the MTHs, presumably leading to a more localized concentration of stress. Furthermore, the addition of dynamic factors in the model, such as fat-pad thickness assessment under dynamic weight-bearing conditions, walking speed, or kinematics of gait, is likely to further improve the prediction of peak plantar pressure.\textsuperscript{14}

Figure 4. Schematic diagram showing the 'exchange' of fat tissue and plantar pressure in the forefoot. While the fat-pad cushion migrates distally, the plantar pressure 'transfers' proximally in the forefoot in patients with claw/hammer toe deformity.

The main function of the toes in gait is to contact the surface and exert sufficient pressure to obtain a fixed point from which the body can be propelled.\textsuperscript{19} This way, the toes help to relieve the MTHs from bearing weight through the distal transfer of load in the final stage before push-off. The toes in the neuropathic subjects with deformity have become less functional by showing a significantly reduced contact area and force-time integral when compared with the toes of the controls. With less functional toes, the MTHs bear an increased amount of weight during propulsion as evidenced by the significant reduction in the toe-loading index found in the patients with deformity. These findings confirm early suggestions by Boulton et al.\textsuperscript{9} that the presence of claw/hammer toes may be responsible for a lower toe-loading ratio found in diabetic subjects compared with healthy controls. Thus, while the fat pad migrates \textit{distally} in the foot\textsuperscript{13} (\textbf{chapter 5}), the load 'migrates' \textit{proximally} in the foot, a process that we call the 'fat pad – plantar pressure exchange principal' (Figure 4).
A limitation of the present study may be that the cross-sectional design does not allow cause-and-effect relationships to be established. High levels of plantar pressure at the MTH may lead to pressure necrosis and fibrotic atrophy, with possible thinning, of sub-MTH fat tissue, but it is unlikely that they cause toe deformity. More likely, the actual sequence of events starts with toe deformity leading to fat-pad displacement, exposing the MTH to increased pressures, as the theory promulgates. The strong correlations found in the present study together with clinical observations by Bojsen-Moller support this conclusion. Prospective studies on this association are difficult to perform because of the unknown natural history of claw/hammer toe deformity - in some patients it may take decades for deformity to develop - and the possibility that over time other deformities may develop which can affect the plantar pressures measured. Our 'model' of comparing similar subjects that differ primarily on one variable of interest (i.e., presence or absence of claw/hammer toe deformity) was therefore regarded as the best way to examine the association between structural abnormalities in the foot and dynamic plantar pressure distribution.

This is the first diabetic foot study in which dynamic barefoot plantar pressure measurements are combined with MRI for evaluating the association between structural changes in the foot and altered gait biomechanics. The results show that MRI may have great potential in diagnosing the at-risk diabetic neuropathic foot, as it does for the neuropathic foot in leprosy. Since these assessments were done non-weight bearing they do not involve the fabrication and use of special equipment needed to image the foot under (quasi) weight-bearing conditions. However, MRI in combination with pressure measurements is not cost-effective in the management of most neuropathic diabetic patients with foot deformity, but may be useful for patients with recurrent or non-healing ulcers by providing insight in the possible mechanism underlying these chronic conditions, and assisting in the design of effective treatment modalities. Moreover, illustrative foot images and plantar pressure graphs of feet at high risk for ulceration may serve an important educational purpose towards better patient compliance.

In conclusion, this study provides quantitative data in support of the long-held belief that claw/hammer toe deformity is associated with elevated plantar pressures in diabetic patients with neuropathy and suggests that distal displacement of the sub-MTH fat-pad cushion is the mechanistic link in this association. The findings contribute to the improvement of our fundamental understanding of the pathogenesis of plantar foot ulceration and, as such, are useful in the diagnosis of the at-risk diabetic patient. Moreover, they emphasize the importance of advancing interventions to accommodate or correct these foot abnormalities or, preferably, prevent them from occurring with the aim of reducing plantar pressures and the risk of ulceration.
Chapter 7

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Elevated plantar pressures in claw/hammer toe deformity

References


Elevated plantar pressures in claw/hammer toe deformity


