We studied the influence of different positions in neighboring joints on strain in the tibial and plantar nerves during ankle and toe movements. Tibial nerve strain at the ankle was measured during ankle dorsiflexion in ten cadavers; plantar nerve strain was measured during toe extension. Tibial nerve strain increased with ankle dorsiflexion (mean increase: 3.9%) and strain was higher when the nervous system was pretensioned by either knee extension or hip flexion ($p \leq .011$). Strain was even higher when the nerve bed was elongated at both the hip and knee ($p \leq .006$) before performing dorsiflexion. A similar trend was observed for the plantar nerves with ankle positioning. In conclusion, the change in nerve strain is strongly influenced by positions in neighboring joints. This insight into nerve biomechanics provides a foundation for progressive mobilization exercises for disorders such as tarsal tunnel syndrome.

**Keywords:** neurodynamics, plantar fascia, plantar heel pain, tarsal tunnel syndrome

Although plantar fasciitis is the most common cause of plantar heel pain (Barrett & O’Malley, 1999; Doxey, 1987), other conditions such as tarsal tunnel syndrome can cause comparable symptoms. Tarsal tunnel syndrome (TTS) is caused by a compression of the tibial or plantar nerves as they pass underneath the flexor retinaculum at the ankle (Lau & Stavrou, 2004). The plantar nerves and the medial calcaneal nerve may also be compressed at more distal locations (Alshami et al., 2008; Govsa et al., 2006).

Conservative treatment strategies for TTS include exercises aimed at mobilization of the tibial nerve and its branches through the tarsal tunnel (Butler, 2000; Meyer et al., 2002). Simple range-of-motion exercises for the foot involve pulling the foot up and pointing it down, and making small inward and outward circles. Besides these simple exercises, more progressive techniques have been described with the lower limb joints in positions that elongate the length of the nerve bed (the tract formed by the structures that surround the nerve) of the tibial and sciatic nerve. Meyer et al. (2002), for example, described a mobilization technique for TTS that involved hip flexion, knee extension, and ankle dorsiflexion. The clinical assumption is that this position pretensions the peripheral nervous system, which may be more beneficial in the later stages of the rehabilitation. However, the impact of these proximal positions on strain in the nerves around the foot and ankle is not well documented.

A few studies have quantified strain and longitudinal movement of the tibial nerve with foot and ankle movements (Alshami et al., 2007; Coppieters et al., 2006; Daniels et al., 1998). For the peroneal nerve, changes in strain during a simulated ankle inversion trauma have been reported (O’Neill et al., 2007). However, there is a dearth of evidence for how a change in nerve strain associated with movement is influenced by the position of neighboring joints. To understand the difference in mechanical impact that various treatment techniques may have on the tibial nerve and its branches, investigation of normal nerve biomechanics in response to joint movements and the influence of neighboring joint positions on changes in strain is warranted.

The primary aim of this study was to investigate how a change in strain in the tibial and plantar nerves during movements of the ankle and toes is influenced by positions in adjacent joints. Because the differential diagnosis of plantar heel pain is challenging (Brown, 1996; Karr, 1994), we also measured changes in strain...
in the plantar fascia during ankle movements. A better understanding of the biomechanics of the tibial and plantar nerves and plantar fascia may contribute to a better insight into the differential diagnosis of plantar heel pain.

Methods

Cadavers

Ten embalmed cadavers (2 females, 8 males; mean ± SD age: 81 ± 7 years), with no signs of trauma or surgery to the limbs or trunk, were selected. Embalming was undertaken within 48 hr of death using a water-based anatomical arterial mixture (Dodge Company, Inc., Cambridge, MA, USA). The cadavers were then stored at 4°C, and a period of six months was allowed for fixation to be completed before measurements were taken. All tests and measurements were performed on the right lower limb with the body at room temperature (21°C). The study was approved by the Institutional Ethics Committee.

Dissection

The dissection was performed in two phases. First, a window of approximately 7 × 4 cm was made into the skin and underlying subcutaneous tissues to expose the tibial nerve behind the medial malleolus. The flexor retinaculum was kept intact. An incision of a similar size was made in the skin and subcutaneous fat in the sole of the foot to expose the plantar fascia. Second, a section of the plantar fascia extending from the medial calcaneal tuberosity to the heads of the metatarsals and the flexor digitorum brevis were excised to expose the medial plantar nerve (MPN) and lateral plantar nerve (LPN). Relevant measurements of nerve strain were performed following each dissection phase.

The Achilles tendon was transected to achieve a physiological range of ankle dorsiflexion. Adequate range of motion at the hip, knee, and toes was obtained by passive through range mobilizations.

Strain Measurements

Differential variable reluctance transducers (DVRTs; MicroStrain, Williston, USA) with a 6-mm linear stroke length and 1.5-µm resolution were used to measure strain. The DVRTs were inserted with barbed pins in the following four structures and locations: (1) for the tibial nerve at the ankle: ~3 cm proximal to the distal tip of the medial malleolus; (2) for the plantar fascia: ~4 cm distal to the medial calcaneal tuberosity; (3) for the MPN: ~8 cm distal to the medial calcaneal tuberosity; and (4) for the LPN: ~5 cm distal to the medial calcaneal tuberosity. Throughout the experiment, the investigator was blind to the output of the DVRTs.

A reference position was used to which the change in strain was expressed. Therefore, the reported strain values are changes relative to the strain in the reference position and are not absolute strain levels. In this reference position, the ankle was positioned in neutral (0 degrees), the knee was in extension (180 degrees) and the hip was in neutral (0 degrees flexion). Calibration equations provided by the manufacturer were used to convert changes in DVRT output (volt) into length changes (millimeter). Subsequently, percentage change for strain was calculated using the following formula: (change in length between the barbed pins of the DVRT / initial length between the barbed pins) × 100.

Test Maneuvers

Strain was recorded during two separate movements: (1) ankle dorsiflexion and (2) extension of the toes. Before performing these two movements, the length of the nerve bed proximal to the moving joint was altered by placing adjacent joints in various positions. All tests were performed with the cadavers in supine.

Ankle Dorsiflexion

The ankle was moved from ~35 degrees plantar flexion to ~15 degrees dorsiflexion. This maneuver was performed with the hip and knee in four different positions:

1. hip in neutral and knee in ~95 degrees flexion (Hipneutral–Knee flex)
2. hip in neutral and knee in extension (Hip neutral–Knee ext)
3. hip in ~70 degrees flexion and knee in ~95 degrees flexion (Hip flex–Knee flex)
4. hip in ~70 degrees flexion and knee in extension (Hip flex–Knee ext)

Of the four investigated positions, Hip neutral–Knee flex is the position in which the nerve bed of the sciatic and tibial nerve is elongated the least, whereas Hip flex–Knee ext is the position with the largest elongation. Changes in strain in the tibial nerve at the ankle and in the plantar fascia were recorded.

Extension of the Toes

The metatarsophalangeal joints of all toes and interphalangeal joint of the first toe were moved from ~20 degrees flexion to ~20 degrees dorsiflexion. With the hip in neutral and the knee in extension, extension of the toes was performed with the ankle in two different positions: (1) ~35 degrees plantar flexion (Hipneutral–Knee ext–AnklePF) and (2) ~15 degrees dorsiflexion (Hipneutral–Knee ext–Ankle ePF). Changes in strain were measured in the MPN and LPN.

Goniometry

A twin-axis electrogoniometer (SG65, Biometrics, Blackwood, UK) was attached to the lateral side of the ankle to continuously measure the range of motion of
the ankle during the experiment. A regular goniometer was used to measure the range of motion of the metatarsophalangeal joints of all toes and the interphalangeal joint of the first toe.

Several devices were used to assist the investigators in maintaining a steady position in the adjacent joints. A twin-axis electrogoniometer (SG110) was attached to the lateral side of the knee to continuously measure the position of the knee. An inclinometer (AccuStar, Schaevitz Sensors, Hampton, USA) was placed on the lateral side of the thigh to measure the position of the hip. One of the advantages of using electrogoniometers and an inclinometer was that real-time feedback could be provided about the movement and position of the joints as well as the possibility to display the target angles via a computer monitor (Figure 1).

Data and Statistical Analysis

Spike2 software (Cambridge Electronic Design, Cambridge, UK) and a data acquisition system (Micro 1401, Cambridge Electronic Design, Cambridge, UK) were used to collect the output from the DVRTs, electrogoniometers, and inclinometer.

For ankle dorsiflexion, the tibial nerve in one cadaver was split into two branches proximal to the medial malleolus and we decided to exclude this cadaver. For toe extension, the DVRTs were unstable in one cadaver because of the very small diameter of the MPN and LPN, which resulted in inconsistent strain recordings. Strain values in the LPN showed extreme outliers that were more than 3 times the interquartile range. Another cadaver had a LPN that was split into three deep and thin branches. The barbed pins of the DVRT had to be inserted through the middle branch of this nerve and impinged on the deeper foot muscles, which affected sliding of the DVRT. In two other cadavers, it was hard to identify the MPN owing to anatomical variation. It was decided not to conduct deeper dissection in these two cadavers to limit alteration of local nerve biomechanics. As a result, recordings from nine cadavers were used for ankle dorsiflexion and from six cadavers for toe extension.

Previous research has demonstrated that changes in nerve strain associated with joint movements can be measured reliably using DVRTs (Byl et al., 2002; Coppieters et al., 2006; Wright et al., 1996). Since we encountered unstable readings for the MPN and LPN with toe extension in one cadaver, the stability of the recordings of the selected six cadavers was evaluated. The intraclass correlation coefficient (ICC[2,1]) and standard error of measurement (SEM) were calculated using strain values of three consecutive repetitions. The reliability coefficients confirmed that the readings from the plantar nerves were stable for the selected cadavers (MPN: ICC[2,1] = 0.93; SEM = 0.21%; LPN: ICC[2,1] = 0.98, SEM = 0.10%).

For each test movement, the mean change in strain of three consecutive measurements was calculated. Changes in strain were analyzed for each structure using a two-way, within-subjects analysis of variance. The first factor was the position of the adjacent joints and the second factor was the position of the moving joint (start and end position). Contrasts and Tukey’s tests for least significant differences were used for multiple comparisons. For all tests, the critical p value was set at 0.05. All data were analyzed using the Statistical Package for the Social Science for Windows (version 13.0, SPSS Inc., Chicago, USA).

Results

Table 1 summarizes the mean (± SD) range of motion of the ankle and the deviations from the target positions for the hip and knee. The range of motion at the ankle was the same for the four different starting positions (p = .535). As can be observed, the adjacent joints were held in a stable position. Only negligible deviations occurred in the hip and knee when the ankle was moved. Table 2 presents the data for toe extension. As for ankle dorsiflexion, deviations from the target position at the ankle, knee, and hip were minimal during movements of the toes.

Figure 1 demonstrates representative data from one cadaver for strain in the tibial nerve and plantar fascia during three consecutive movements of the ankle. Data for two starting positions are presented (Hipflex–Kneeext and Hipneutral–Kneeext). For the tibial nerve, clear changes in strain can be observed with ankle movements, with a higher baseline and higher peaks when the peripheral nervous system is pretensioned by hip flexion (Hipflex– Kneext). For the plantar fascia, the baseline and peaks are similar for the two conditions.

Figure 2A illustrates the change in strain in the tibial nerve at the ankle with ankle dorsiflexion. As anticipated, strain in the tibial nerve increased significantly with ankle dorsiflexion (p = .002). Significant differences in strain in the tibial nerve at the ankle were observed for different positions of the hip and knee (p = .001). The strain in the tibial nerve at the ankle during dorsiflexion was the smallest when the peripheral nervous system was unloaded at the adjacent joints (Hipneutral–Knee flex; p ≤ .011). Compared with this unloaded condition, the strain associated with ankle dorsiflexion was larger with either the hip or knee in a position that elongated the nerve bed (Hipflex–Knee flex; p = .011; Hipneutral–Knee flex; p = .005). There was no difference in strain between the two conditions in which the nerve bed was elongated at one joint, that is, with either hip flexion or knee extension (Hipflex–Knee flex versus Hipneutral–Knee ext; p = 0.168). The largest amount of strain with ankle dorsiflexion was observed when the nerve bed was elongated at both the hip and knee (Hipflex–Knee ext; p ≤ .006). Strain in the plantar fascia (Figure 2B) also increased significantly with ankle dorsiflexion (p = .011), but was not different with different positions of the hip and knee (p = .181).
Figure 1 — Representative raw data from one cadaver during ankle movements in two different positions of the hip and knee. In the left panels, the nerve bed is submaximally elongated (hip flexion and knee extension). In the right panels, the nerve bed is less elongated (hip neutral and knee extension). Note that although the movement at the ankle is identical in both conditions, the amount of strain in the tibial nerve is markedly different. For the knee, 180° corresponds with full extension. SiRP: strain in reference position.
The main finding of the current study is that the amount of nerve strain at the foot and ankle associated with ankle and toe movements is strongly influenced by the position of neighboring joints. During ankle dorsiflexion, strain in the tibial nerve at the tarsal tunnel is the lowest when the positions of both the hip and knee do not pretension the sciatic or tibial nerve. When the nerve bed of the sciatic or tibial nerve is elongated at either the hip or knee, the strain in the tibial nerve at the ankle increases significantly. Strain during ankle dorsiflexion is further increased when the peripheral nervous system is pretensioned at both the hip and knee. Similarly, strain in the MPN and LPN during toe extension is larger with the ankle in dorsiflexion than in plantar flexion. These findings clearly demonstrate the cumulative effect that neighboring joints may have on strain in the nervous system. Increases in nerve strain following elongation of the nerve bed can be transmitted and distributed over long sections of the peripheral nervous system, for example, along the sciatic and tibial nerve between the hip and ankle.

Table 1  The Mean (± SD) Range of Motion of the Ankle and the Deviations From the Target Positions of the Neighboring Joints During Movement of the Ankle (n = 9)

<table>
<thead>
<tr>
<th>Range of movement</th>
<th>Deviation at adjacent joint</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hip&lt;sub&gt;neutral&lt;/sub&gt;–Knee&lt;sub&gt;flexion&lt;/sub&gt;</td>
<td>52.0 ± 11.1</td>
</tr>
<tr>
<td>Hip&lt;sub&gt;neutral&lt;/sub&gt;–Knee&lt;sub&gt;extension&lt;/sub&gt;</td>
<td>51.7 ± 11.4</td>
</tr>
<tr>
<td>Hip&lt;sub&gt;flexion&lt;/sub&gt;–Knee&lt;sub&gt;flexion&lt;/sub&gt;</td>
<td>52.1 ± 11.8</td>
</tr>
<tr>
<td>Hip&lt;sub&gt;flexion&lt;/sub&gt;–Knee&lt;sub&gt;extension&lt;/sub&gt;</td>
<td>51.9 ± 11.6</td>
</tr>
</tbody>
</table>

Note. The values are in degrees. The ankle was moved from plantar flexion to dorsiflexion. Note that deviations in the position of the hip and knee during ankle movements were negligible.

Table 2  The Mean (± SD) Range of Motion of the Toes and the Deviations from the Target Positions of the Neighboring Joints During Movement of the Toes (n = 6)

<table>
<thead>
<tr>
<th>Range of movement</th>
<th>Deviation at adjacent joint</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st MTP</td>
<td>1st IP</td>
</tr>
<tr>
<td>Ankle</td>
<td>Knee</td>
</tr>
<tr>
<td>Hip&lt;sub&gt;neutral&lt;/sub&gt;–Knee&lt;sub&gt;extension&lt;/sub&gt;–Ankle&lt;sub&gt;foot&lt;/sub&gt;</td>
<td>40.8 ± 7.4</td>
</tr>
<tr>
<td>Hip&lt;sub&gt;neutral&lt;/sub&gt;–Knee&lt;sub&gt;extension&lt;/sub&gt;–Ankle&lt;sub&gt;foot&lt;/sub&gt;</td>
<td>40.8 ± 7.4</td>
</tr>
</tbody>
</table>

Note. The values are in degrees. The toes were moved from flexion to extension. Note that deviations from the target position of the ankle, knee, and hip during movement of the toes were minimal. Because it was impossible to measure the range of motion of the toes during the tests, the available amplitude was measured before the tests. This explains the identical amplitudes of the toes for both conditions. MTP: metatarsophalangeal joint; IP: interphalangeal joint; PF: plantar flexion; DF: dorsiflexion.

Discussion

The main finding of the current study is that the amount of nerve strain at the foot and ankle associated with ankle and toe movements is strongly influenced by the position of neighboring joints. During ankle dorsiflexion, strain in the tibial nerve at the tarsal tunnel is the lowest when the positions of both the hip and knee do not pretension the sciatic or tibial nerve. When the nerve bed of the sciatic or tibial nerve is elongated at either the hip or knee, the strain in the tibial nerve at the ankle increases significantly. Strain during ankle dorsiflexion is further increased when the peripheral nervous system is pretensioned at both the hip and knee. Similarly, strain in the MPN and LPN during toe extension is larger with the ankle in dorsiflexion than in plantar flexion. These findings clearly demonstrate the cumulative effect that neighboring joints may have on strain in the nervous system. Increases in nerve strain following elongation of the nerve bed can be transmitted and distributed over long sections of the peripheral nervous system, for example, along the sciatic and tibial nerve between the hip and ankle.

The majority of the studies investigating the effects of joint positioning on nerve strain has focused on the upper limb (e.g., Coppiters & Alshami, 2007; Coppiters & Butler, 2008; Kleinrensink et al., 2000; Wright et al., 2001). To the authors’ knowledge, there is only one other study that evaluated the impact of neighboring joint positions on nerve strain in the lower limb. In a perioperative study, Fleming et al. (2003) examined the effect of hip position on strain in the sciatic nerve during knee movements. The strain in the sciatic nerve during knee extension was significantly larger when the hip was positioned in 45 degrees flexion compared with when the hip was in a neutral position. These recordings from a more proximal part of the nerve at the level of the hip are in agreement with our findings obtained from more distal measurements at the foot and ankle.
Figure 2 — Changes in strain in the tibial nerve around the ankle (A) and in the plantar fascia (B) during ankle dorsiflexion for four different positions of the hip and knee ($n = 9$). Note that hip and knee positions influence the strain in the tibial nerve at the ankle with dorsiflexion but have no effect on the amount of strain in the plantar fascia. Error bars represent 1 SD. SiRP: strain in reference position.

Figure 3 — Changes in strain in the medial (A) and lateral (B) plantar nerve during toe extension for two different positions of the ankle ($n = 6$). Error bars represent 1 SD. SiRP: strain in reference position; DF: dorsiflexion; PF: plantar flexion.
The position of the joints of the limb and spine must be considered during clinical assessment because the cumulative in situ strain of a peripheral nerve is a direct reflection of the positioning across multiple joints (Topp & Boyd, 2006). The dorsiflexion-eversion test (DF-Ev test) has recently been devised to diagnose TTS (Kinoshita et al., 2001). In this test, the ankle is passively dorsiflexed, the foot is everted, and all metatarsophalangeal joints are extended. The findings of the current study indicate that to standardize the DF-Ev test, the position of the hip and knee need to be considered. Furthermore, the test may be more sensitive in the diagnosis of minor neuropathies if the DF-Ev test is performed in hip flexion and knee extension (straight leg raising position) or when sitting in spinal flexion, hip flexion, and knee extension (the slump test position). In a case study, Meyer et al. (2002) were able to reproduce a patient’s burning pain and tightness in the heel and medial arch with the DF-Ev test in a straight leg raising position.

Besides clinical tests for TTS, the position of adjacent joints may also be important in the assessment of other disorders that cause plantar heel pain. The Windlass test has been devised to diagnose plantar fasciitis and consists of passive extension of either the first or all metatarsophalangeal joints with the ankle in neutral (Brown, 1996). De Garceau et al. (2003) investigated the diagnostic validity of the Windlass test in both weight-bearing (standing) and non-weight-bearing (sitting) positions. A higher sensitivity of the Windlass test in the standing position was explained by the fact that weight bearing prestretches the plantar fascia (De Garceau et al., 2003). Recent research has demonstrated that the Windlass test loads not only the plantar fascia but also the tibial and plantar nerves (Alshami et al., 2007). Although the higher proportion of positive tests when the Windlass test is performed in standing may be explained by a prestretch of the plantar fascia (De Garceau et al., 2003), an alternative explanation may be that the tibial nerve and its branches around the foot and ankle may also be prestretched in standing (knee extension). This alternative explanation seems plausible because De Garceau et al. (2003) acknowledged that their patients may have had additional etiologies for their pain, such as compression neuropathies of the branches of the tibial nerve. Obviously, care is warranted with the extrapolation of anatomical/biomechanical findings to clinical situations. Another limitation of the interpretation of the results is that we performed the tests in supine whereas De Garceau et al. (2003) performed the tests in a weight-bearing position.

Peripheral nerve inflammation and compression may contribute to the symptoms of patients presenting with plantar heel pain (Saggini et al., 2007). In addition to reduction of inflammation and nerve compression, therapeutic strategies can be included to restore the capacity of the nervous system to slide relative to its surrounding structures and to tolerate nerve strain that will occur normally during limb movement (Topp & Boyd, 2006). Treatment techniques for patients with TTS that include knee movements and mobilization exercises that pretension the nervous system by including hip and spinal flexion have been described (Meyer et al., 2002; Shacklock, 1995). The present study demonstrates that strain in the tibial nerve at the tarsal tunnel can be progressively increased by incorporating the knee and hip in mobilization exercises and provides quantitative data to extend the extent of the changes in strain.

The findings of the study also reveal the remarkable changes in strain that a healthy nervous system is able to tolerate during certain activities. For example, when jumping over a hurdle, the lead leg is moved from hip extension and knee flexion into hip flexion, knee extension and ankle dorsiflexion with the lumbar and thoracic spine in flexion. Our study demonstrates that strain in the tibial nerve at the tarsal tunnel is 8.3% (±4.1) higher (from −4.6 to 3.6, see Figure 2A) with the hip in flexion, the knee in extension, and the ankle in dorsiflexion compared with a combined position of hip in neutral, knee in flexion, and the ankle in plantar flexion. When a nerve is inflamed, low levels of strain (~3%) and compression are sufficient to generate ectopic impulses and possibly symptoms (Dilley et al., 2005). Although this study focused on changes in strain and the impact of adjacent joint positions, previous studies have reported an increase in tarsal tunnel pressure with foot and ankle positions (Trepman et al., 1999). In addition to tarsal tunnel pressures, Barker et al. (2007) observed a significant increase in pressure in the medial and lateral plantar tunnel with pronation.

The secondary aim of this study was to investigate changes in strain in the plantar fascia. Alshami et al. (2007) found that strain increased in not only the plantar fascia but also in the tibial and plantar nerves during either extension of the toes or dorsiflexion of the ankle. In the current study, strain increased with ankle dorsiflexion but, as anticipated, strain in the plantar fascia was not influenced by the position of the hip or knee. This is consistent with a previous study that demonstrated that straight leg raising results in a significant increase in strain in the tibial nerve at the ankle, but does not influence the plantar fascia (Coppieters et al., 2006). Awareness of the different mechanical behavior of the plantar fascia compared with the tibial nerve at the tarsal tunnel may assist in the differential diagnosis of patients with plantar heel pain. A limitation of the interpretation of strain in the plantar fascia is, however, that the Achilles tendon was transected to obtain a physiological range of ankle dorsiflexion. Since myofascial force transmission has been described in animal research (Rijkeljikhuizen et al., 2005) and continuity via a bone-fascia-tendon model has been described (Gerlach & Lierse, 1990), a possible effect of proximal joint positioning on strain in the plantar fascia may have been overlooked. However, to our knowledge, force transmission along a myofascial system from the hip or knee to the foot has not been investigated to date. In future experiments, it might be useful to investigate whether
changes in strain in the plantar fascia occur during smaller ankle movements, but with the Achilles tendon intact.

Besides the transection of the Achilles tendon, skin, subcutaneous tissues and fascia had to be removed to be able to make strain recordings of the deeper tissues. Although all dissections were carefully planned to minimize disruption of surrounding soft tissues and local biomechanics, the dissection may of course have affected the strain measurements to some degree.

In conclusion, the study demonstrates that the position of adjacent joints has a substantial impact on the amount of strain in the tibial and plantar nerves during movements of the foot and ankle. This knowledge is important to appreciate normal nerve biomechanics around the foot and ankle during activities and to better understand possible pathomechanisms of nerve disorders. In addition, a better understanding of nerve biomechanics will contribute to a better insight in clinical diagnostic tests and treatment strategies for nerve disorders, such as TTS.

References


