Tibial nerve dynamics during ankle dorsiflexion: Using ultrasonographic stiffness to measure excursion

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Abstract

Decreased nerve mobility and increased nerve stiffness have been proposed as causes of tarsal tunnel syndrome and diabetic neuropathy. The purpose of this study was to measure the stiffness of the tibial nerve (TN) at the ankle joint at positions of plantarflexion (PF) and dorsiflexion (DF) and the mobility (excursion) of the TN during dorsiflexion using shear-wave elastography ultrasonography. Twenty-one healthy adults participated in constant-velocity movements of the ankle joint from the maximum dorsiflexion angle to -20°, and the TN was imaged using an ultrasound imaging system. The maximum flow velocity value and the TN excursion distance per dorsiflexion were then calculated as indexes of excursion using the application software Flow PIV. The shear-wave velocities of the TN at PF and DF were also measured. We observed a relationship between the TN excursion and stiffness that was stronger at 25% dorsiflexion than at 75% dorsiflexion. In addition, the ultrasonographic shear-wave velocity could predict the excursion of the TN if measured under mild plantar flexion of the ankle joint (i.e., 25% dorsiflexion).

Introduction

Peripheral nerves such as the tibial nerve (TN) have "neurodynamics." They can glide and extend within the surrounding tissues to adapt to joint movements, which is necessary for maintaining the physiological function of the nerve[1]. Recently, abnormalities in neurodynamics have been evaluated quantitatively using ultrasound imaging[2, 3]. Decreased excursion ability and increased stiffness of the TN are proposed as causes of tarsal tunnel syndrome and diabetic neuropathy[4, 5]. Therefore, we need a method of evaluating TN excursion and stiffness that can easily be applied in clinical practice.

Nerve excursion is evaluated based on the extent of nerve movement seen in ultrasound imaging, but this method has the disadvantage of requiring a large amount of time for analysis and the data are therefore difficult to evaluate in real time[2, 3, 6]. TN stiffness can be assessed using shear-wave elastography (SWE) [7−9], but few studies have focused on determining the ankle positions valid for such measurements, the choice of which may affect stiffness. Moreover, elucidating the effect of stiffness on excursion at the TN can lead to a better understanding of the best ankle positions to use for the simultaneous ultrasonographic evaluation of excursion and stiffness. However, the in vivo relationships between the TN excursion and stiffness remain unclear.

This study aimed to measure the stiffness of the TN in the ankle joint at plantar flexion and dorsiflexion positions and its excursion during ankle dorsiflexion motion. We hypothesized that a significant relationship exists between TN excursion properties and stiffness, and measuring TN stiffness in ankle plantar flexion rather than in dorsiflexion better reflects TN excursion properties. The results confirmed such a relationship, and shear-wave velocity measured under mild plantar flexion could evaluate TN excursion.

Methods

Participants

We investigated 24 right ankles from healthy adults. We recruited individuals with no low-back or lower limb pain and no history of lumbar disc herniation. Three ankles were excluded because the TN stiffness was too great to be measured by SWE. Therefore, we included 21 right ankles (10 men and 11 women; mean age, 20.8 ± 0.5 y; height, 164.2 ± 8.6 cm; weight, 58.8 ± 12.5 kg).

Ethical approval was granted by the ethics committee of Morinomiya University of Medical Sciences (#2021-069), and all procedures were performed in accordance with the Declaration of Helsinki. Informed consent was obtained from all participants before testing.

In all participants, the ankle plantarflexion angle at rest and the maximum ankle dorsiflexion angle (Max-df) were measured to determine the range of angles useful for analysis of TN excursion and stiffness. The first angle was measured using a goniometer when both feet were lowered from the edge of a bed starting from a supine position. The Max-df was measured using a robotic dynamometer (Biodex System 4; Biodex Medical System Inc., Shirley, NY, USA), with the participant's trunk and neck in the intermediate position, the hip in 90° flexion, and the knee in 30° flexion.

TN stiffness in ankle dorsiflexion

TN stiffness was assessed using the SWE mode of an ultrasound imaging system (Aplio 300, Canon Medical Systems, Tokyo, Japan) with a 10-MHz linear transducer (PLT-1005BT, Toshiba, Tokyo, Japan). Shear-wave velocity (SWV) was measured at two ankle positions, 25% and 75% of the dorsiflexion angle (25% df-SWV and 75% df-SWV, respectively), which were calculated from the total ankle range of motion based on the sum of the rest plantarflexion angle and the Max-df. During measurement, these ankle positions were set using the Biodex 4, with the trunk and neck in the intermediate position, the hip in 90° flexion, and the knee in 30° flexion. Images were acquired at 1 cm proximal to the superior edge of the medial malleolus[7]. Long-axis images of the TN were acquired in imaging mode (Figure 1**a**) and particle velocimetric mode (Fig. 1**b**). The measurement site was marked with an oil-based pen. The SWV (m/s) was measured at three regions of interest randomly set in the TN, and the average value was calculated to represent the TN stiffness. To validate this measurement, six participants (five men and one woman; age, 21.0 ± 0.0 y; height, 168.2 ± 8.4 cm; weight, 60.2 ± 12.1 kg) were measured twice with an interval of one week between measurements. The stiffness intraclass correlation coefficients (ICCs) and 95% confidence intervals for the minimum detectable change (MDC_{95}) were then calculated for each measurement condition.

TN excursion during ankle dorsiflexion

Using the ultrasonography system described above, we recorded movies of TN movement in real time. During measurement, the linear transducer was fixed to the measurement site, which was the same as in the stiffness evaluation, with a thermoplastic fixture and an elastic bandage. The Biodex System 4 was used to passively move the ankle from 20° plantarflexion to the Max-df while the participant's neck and trunk were in the neutral position, the hip was in 90° flexion, and the knee was in 30° flexion. The ankle was moved at a constant velocity of 30°/s; 0.67 s was allowed for each of dorsiflexion and plantar flexion, and 0.33 s was allowed for switching the direction of movement.

The movies were analyzed by particle image velocimetry, an optical technique for measuring the displacement of a particle pattern, using the application software Flow PIV (Library, Inc., Tokyo, Japan) in accordance with a previously verified method[8]. Flow PIV can isolate the relative pixel motion between successive frames of an ultrasound movie to visualize flow direction and velocity. Five regions of interest (21 × 15 pixels each, 0.0165 s per frame, 2-frame intervals) were set in the TN for tracking nerve motions (Figure 1**c**). The framewise mean of the flow velocity value and its time series were recorded (Figure 2). The maximum flow velocity values observed in the time-series data during three dorsiflexions of the same nerve were averaged and used as the maximum flow velocity value for analysis (Max-FV). Additionally, the distances obtained by multiplying each flow velocity value by a frame interval of 0.033 s were summed over a flexion cycle and the average of this sum over three successive flexions was defined as the TN excursion distance per dorsiflexion (TN-ED). The validation group comprised eight participants (three men and five women; age, 21.0 ± 0.0 y; height, 163.9 ± 9.5 cm; weight, 59.9 ± 12.5 kg), who were measured twice with an interval of 1 week between measurements. As before, the ICCs and MDC_{95}s were calculated from these data for each measurement condition.

Statistical analysis

SPSS Statistics 24.0 for Windows (IBM, Armonk, NY, USA) was the statistical software. The distributions of the 25% df-SWV, 75% df-SWV, Max-df, Max-FV, and TN-ED consistently passed the Shapiro–Wilk normality test. Therefore, all data are presented as mean ± standard deviation (SD). A two-tailed paired t-test -was performed to examine the differences between the 25% df-SWV and the 75% df-SWV with significance level $p < 0.05$. Additionally, a single-regression analysis was performed with Max-FV and TN-ED as the dependent variables and 25% df-SWV, 75% df-SWV, and Max-df as the independent variables, to clarify the influence of changes in the TN stiffness on its excursion. The statistical significance level of this test was also $p < 0.05$. The ICC[1,2] and MDC_{95} were calculated to measure the reliability of the TN stiffness and excursion determinations. The MDC_{95} was calculated as: $MDC_{95} = SEM \times \sqrt{2} \times 1.96$.

Results

The ankle plantarflexion angle at rest was 28.1 ± 3.7° and the Max-df was 19.3 ± 5.9°. Therefore, the 25% df-SWV was measured at -16.1 ± 3.7° ankle dorsiflexion and the 75% df-SWV was measured at 7.8 ± 4.9° ankle dorsiflexion. The 75% df-SWV was significantly greater than the 25% df-SWV (7.4 ± 0.7 m/s versus 5.5 ± 1.3 m/s, $p < 0.001$). In addition, the Max-FV was 10.2 ± 0.8 mm/s and the TN-ED was and 8.3 ± 0.7 mm.

Regression analysis

Single-regression analysis revealed that both the 25% df-SWV and the 75% df-SWV had a significant correlation with both the Max-FV and the TN-ED, but the Max-df did not have a significant correlation (Table 1). The adjusted R^2 and the standardized regression coefficient β values showed that the correlations of 25% df-SWV with Max-FV (adjusted R^2, 0.69; β, -0.84; $p < 0.001$) and with TN-ED (adjusted R^2, 0.48; β, -0.71; $p < 0.001$) were stronger than those of 75% df-SWV (Max-FV: adjusted R^2, 0.32; β, -0.59; $p = 0.005$; TN-ED: adjusted R^2, 0.22; β, -0.51; $p = 0.019$).

Table 1. Statistical relationships between tibial nerve (TN) stiffness and excursion

	Max-FV			TN-ED		
	Adjusted R^2	β	p-value	Adjusted R^2	β	p-value
25% df-SWV	0.69	-0.84	<0.001	0.48	-0.71	<0.001
75% df-SWV	0.32	-0.59	0.005	0.22	-0.51	0.019
Max-df	0.18	+0.42	0.058	0.06	+0.33	0.150

Abbreviations: Max-FV, the maximum flow velocity of the TN; TN-ED, the TN excursion distance per dorsiflexion cycle; 25% df-SWV, the shear-wave velocity of the TN measured at 25% dorsiflexion of the total ankle range; 75% df-SWV, the same measured at 75% dorsiflexion of the total ankle range; Max-df, the maximum dorsiflexion range of motion of the ankle. Max-FV and TN-ED are dependent variables in a single-regression analysis.

Repeatability and sensitivity

The ICCs[1,2] of 25% df-SWV, 75% df-SWV, Max-FV, and TN-ED were, respectively, 0.96 (95% CI, 0.77–0.99), 0.95 (0.67–0.99), 0.91 (0.57–0.98), and 0.95 (0.79–0.99).

The SEMs of 25% df-SWV, 75% df-SWV, Max-FV, and TN-ED were, respectively, 0.24, 0.32, 0.18, and 0.22. The corresponding MDC_{95} values were 0.67, 0.89, 0.51, and 0.61.

Discussion

The present study revealed that both the 25% df-SWV and the 75% df-SWV significantly correlated with both the Max-FV and the TN-ED, and the correlation of 25% df-SWV with excursion was stronger than that of 75% df-SWV. Therefore, TN stiffness in plantar flexion (i.e., 25% df) reflected TN excursion. These findings support our hypothesis.

To date, a relationship between TN excursion and stiffness has only been identified in cadaveric studies[9–11], although excursion and stiffness have been evaluated individually using *in vivo* ultrasonography[12–14]. Therefore, this may be the first study to show that SWV measurements in the ankle plantar flexion position reflect the excursion of the TN, in addition to showing the effect of peripheral nerve stiffness on excursion *in vivo*. The nerve trunks and fascicles of peripheral nerves normally exist in a relaxed state, and stretching stimulation first facilitates nerve excursion, then increases the nerve tension[1]. Therefore, our results showed that while the 75% df-SWV was greater than the 25% df-SWV, the latter was more strongly related to the excursion.

The present study is clinically relevant because it provides useful information on the evaluation of TN dynamics. The evaluation of peripheral nerve excursion requires the analysis of the amount of nerve movement seen in ultrasound images, which is difficult to accomplish in real time. The results suggest that measuring SWV at 25% df in real time can be used to evaluate dynamic nerve stiffness and thus TN excursion.

The present study had several limitations. First, since TN excursion was assessed after confining the test range of motion of the ankle joint to 20°, we could not investigate the complete range of dynamics of the peripheral nerve from tortuosity to stiffness. Second, in the measurement of SWV using SWE, three participants had TN stiffnesses too high to be measured. Therefore, evaluation of peripheral nerve dynamics by SWE may not be possible for all participants. Third, since this study was conducted only on healthy participants, our conclusions could not be validated in patients. In the future, it will be necessary to evaluate these neurodynamics in patients with peripheral neuropathy.

To summarize, we observed a relationship between TN excursion and stiffness, and the relationship was stronger for 25% df-SWV than for 75% df-SWV. Moreover, SWV measured under mild plantar flexion of the ankle joint could predict the excursion of the TN.

Abbreviations

FDL, flexor digitorum longus; FHL, flexor hallucis longus; ICC, intraclass correlation coefficient; Max-df, maximum ankle dorsiflexion angle; Max-FV, maximum flow velocity; MDC95, 95% confidence interval of the minimal detectable change; SD, standard deviation; SEM, standard error of the mean; SWE, shear-wave elastography; SWV, shear-wave velocity; 25% df-SWV, SWV measured at 25% dorsiflexion; 75% df-SWV, SWV measured at 75% dorsiflexion; TN, tibial nerve; TN-ED, tibial nerve excursion distance per dorsiflexion

Declarations

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Author contributions

Design of text, acquisition of data, data analysis, interpretation and drafting of the manuscript: K.A. Acquisition of data and data analysis: M.N., M.I. and S.K. Critical revision of the manuscript and approval of the article: K.K., M.T. and S.K. All authors have read and agreed to the published version of the manuscript.

Data availability

All data generated or analyzed during this study are included in this published article.

Competing interests

The authors declare no competing interests.

References

1. Sunderland, S. S. The anatomy and physiology of nerve injury. Muscle Nerve **13**, 771–784 (1990).
2. Sierra-Silvestre, E., Bosello, F., Fernández-Carnero, J., Hoozemans, M. J. M. & Coppieters, M. W. Femoral nerve excursion with knee and neck movements in supine, sitting and side-lying slump: an in vivo study using ultrasound imaging. Musculoskelet. Sci. Pract. **37**, 58–63 (2018).
3. Shum, G. *et al.* Decreased tibial nerve movement in patients with failed back surgery syndrome and persistent leg pain. Eur. Spine J. **28**, 2122–2128 (2019).
4. Boyd, B. S., Gray, A. T., Dilley, A., Wanek, L. & Topp, K. S. The pattern of tibial nerve excursion with active ankle dorsiflexion is different in older people with diabetes mellitus. Clin. Biomech. (Bristol Avon) **27**, 967–971 (2012).
5. He, Y., Xiang, X., Zhu, B. H. & Qiu, L. Shear wave elastography evaluation of the median and tibial nerve in diabetic peripheral neuropathy. Quant. Imaging Med. Surg. **9**, 273–282 (2019).
6. Shum, G. L., Attenborough, A. S., Marsden, J. F. & Hough, A. D. Tibial nerve excursion during lumbar spine and hip flexion measured with diagnostic ultrasound. Ultrasound Med. Biol. **39**, 784–790 (2013).
7. Carroll, M., Yau, J., Rome, K. & Hing, W. Measurement of tibial nerve excursion during ankle joint dorsiflexion in a weight-bearing position with ultrasound imaging. J. Foot Ankle Res. **5**, 5 (2012).
8. Kawanishi, K. & Kudo, S. Quantitative analysis of gliding between subcutaneous tissue and the vastus lateralis – influence of the dense connective tissue of the myofascia. J. Bodyw. Mov. Ther. **24**, 316–320 (2020).
9. Alshami, A. M., Babri, A. S., Souvlis, T. & Coppieters, M. W. Biomechanical evaluation of two clinical tests for plantar heel pain: the dorsiflexion-eversion test for tarsal tunnel syndrome and the windlass test for plantar fasciitis. Foot Ankle Int. **28**, 499–505 (2007).
10. Alshami, A. M., Babri, A. S., Souvlis, T. & Coppieters, M. W. Strain in the tibial and plantar nerves with foot and ankle movements and the influence of adjacent joint positions. J. Appl. Biomech. **24**, 368–376 (2008).

11. Bueno-Gracia, E. *et al.* Differential movement of the sciatic nerve and hamstrings during the straight leg raise with ankle dorsiflexion: implications for diagnosis of neural aspect to hamstring disorders. Musculoskelet. Sci. Pract. **43**, 91–95 (2019).
12. Andrade, R. J. *et al.* Non-invasive assessment of sciatic nerve stiffness during human ankle motion using ultrasound shear wave elastography. J. Biomech. **49**, 326–331 (2016).
13. Andrade, R. J. *et al.* The potential role of sciatic nerve stiffness in the limitation of maximal ankle range of motion. Sci. Rep. **8**, 14532 (2018).
14. Andrade, R. J. *et al.* Chronic effects of muscle and nerve-directed stretching on tissue mechanics. J. Appl. Physiol. (1985) **129**, 1011–1023 (2020).

Figures

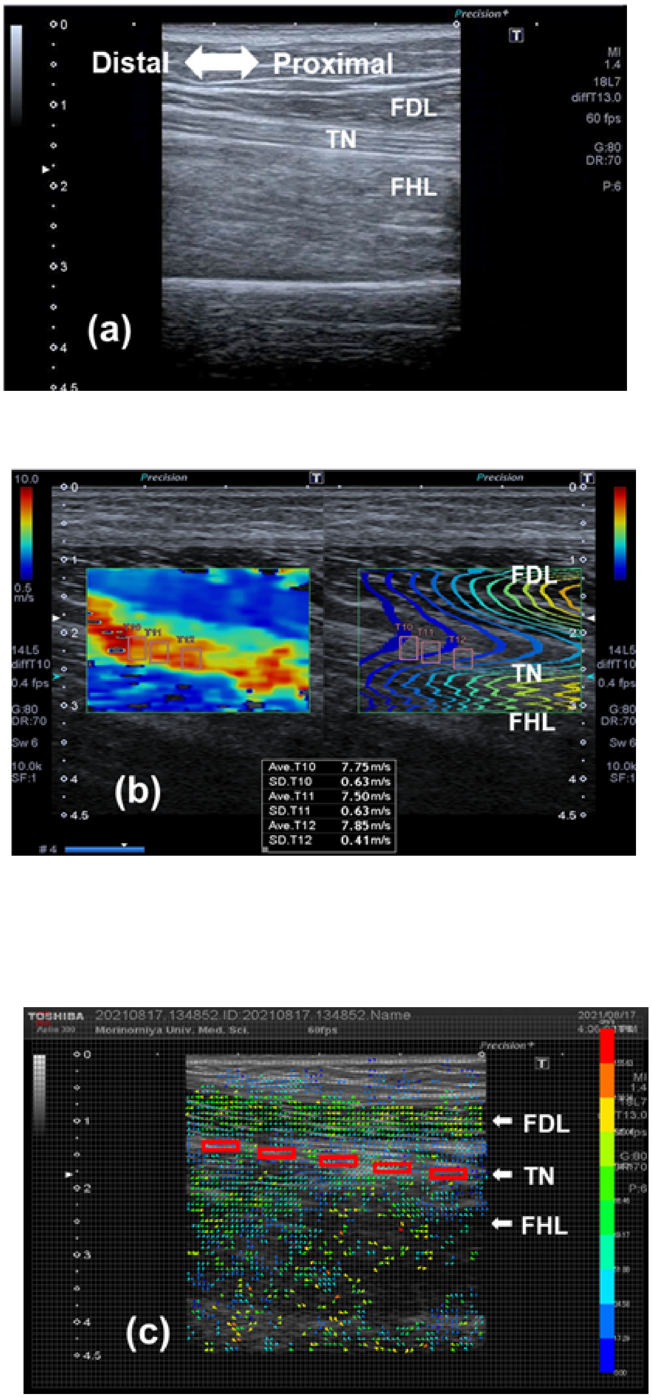

Figure 1

Ultrasound images for evaluating tibial nerve (TN) excursion and stiffness

a. Long-axis image of the TN. **b.** Particle image velocimetry analysis of Figure 1**a** for the excursion evaluation. Five regions of interest are placed within the TN. **c.** Shear-wave elastographic image. Three regions of interest are placed within the TN. FDL, flexor digitorum longus; FHL, flexor hallucis longus.

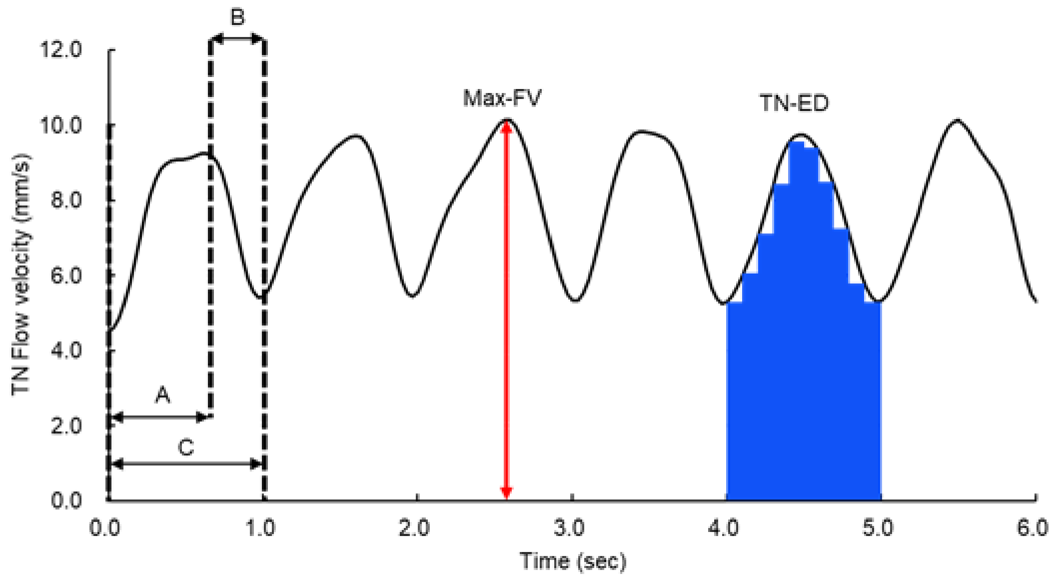

Figure 2

Method of evaluating tibial nerve (TN) excursion

Shown is the TN flow velocity plotted against time. A, ankle dorsiflexion exercise time (0.67 s); B, rest time (0.33 s); C, ankle dorsiflexion movement phase (1.0 s); Max-FV, maximum flow velocity value of the TN; TN-ED, TN excursion distance per dorsiflexion.