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Short communication

Shear and pressure under the first ray in neuropathic diabetic patients: Implications for support of the longitudinal arch

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ABSTRACT

Objective: To assess dynamic arch support in diabetic patients at risk for Charcot neuroarthopathy whose arch index has not yet shown overt signs of foot collapse.
Methods: Two indirect measures of toe flexor activation (ratios: peak hallux pressure to peak metatarsal pressure – Ph/Pm; peak posterior hallux shear to peak posterior metatarsal shear – Sh/Sm) were obtained with a custom built system for measuring shear and pressure on the plantar surface of the foot during gait. In addition, the tendency of the longitudinal arch to flatten was measured by quantifying the difference in shear between the 1st metatarsal head and the heel ($S_{flatten}$) during the first half of the stance phase. Four stance phases from the same foot for 29 participants (16 control and 13 neuropathic diabetic) were assessed.
Results: The peak load ratio under the hallux (Ph/Pm) was significantly higher in the control group (2.10 ± 1.08 versus 1.13 ± 0.74, $p=0.033$). Similarly, Sh/Sm was significantly higher in the control group (1.87 ± 0.88 versus 0.88 ± 0.45, $p=0.004$). The difference in anterior shear under the first metatarsal head and posterior shear under the lateral heel ($S_{flatten}$) was significantly higher in the diabetic group ($p < 0.01$). Together these findings demonstrate reduced plantar flexor activity in the musculature responsible for maintaining the longitudinal arch.
Conclusions: With no significant difference in arch index between the two groups, but significant differences in Ph/Pm, Sh/Sm and $S_{flatten}$ the collective results suggest there are changes in muscle activity that precede arch collapse.

1. Introduction

In feet that are anatomically and physiologically fully functional, toe flexor muscles and aponeurosis tensions produce metatarsal joint loadings that support the longitudinal arch of the foot. The forces that act through the metatarsophalangeal joints have implications in our understanding of pain and degeneration at these joints (Mueller et al., 2003). At particular risk are heavily loaded regions overlying bony prominences, such as under the metatarsal heads where the majority of plantar neuropathic ulcers occur (Lord and Hosein, 2000). Patients with a history of first metatarsal head ulceration have significantly less first ray mobility and significantly higher pressure at the first metatarsal head compared with the other groups (Birke et al., 1995; Mueller et al., 1989). Stiffness of the foot and ankle joints in diabetic patients has been shown to increase forefoot pressures (Birke et al., 1995; Delbridge et al., 1988; Mueller et al., 2003).

Charcot neuroarthropathy is a joint disease that results in permanent foot deformity with more than 70% of cases involving the first ray and midfoot (Lee and Davis, 2009). An issue with studying the biomechanics of arch support and the etiology of longitudinal arch collapse is that there is a potential "chicken and egg" situation, namely an arch that has collapsed could restrict the ability of muscles to offer dynamic support to the arch, and conversely, muscle atrophy could lead to a collapsed arch. Aside from muscular support, it is possible that connective tissue changes in diabetic patients (that are associated with stiffer joints) could provide support for transverse and longitudinal arches of the foot. What is not known is the interplay between muscular and ligamentous factors in the dynamic support of the arch in patients with diabetes.

This experiment focuses on the mechanics of arch support in neuropathic patients prior to any overt signs of arch collapse. Indicators of toe flexor activity can be obtained by measuring

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pressure and shear forces under the hallux and first metatarsal head during gait (Stokes et al., 1979). It is hypothesized that the inactivity of flexor muscles, mainly flexor hallucis longus, will decrease the toe/1st metatarsal head (MTH) load ratios for both pressure and shear as generally seen in healthy patients. Less pressure and posterior shear under the hallux region are predicted among diabetic subjects due to the inadequacy of the long flexor muscle to perform a posterior pull and the concomitant tendency of the toe to plantar-flex during gait. Furthermore, in this scenario, it would be expected that the tendency of the foot to flatten could be assessed by simultaneously comparing the posterior shear under the heel with the anterior shear under the first MTH. With diminished dynamic support of the arch, the differences in these shear forces ($S_{flatten}$) would be expected to be elevated in diabetic neuropathic patients.

2. Materials and methods

Data were collected on 29 human subjects: 16 control (9 M, 7 F, age: 47.6 ± 5.8 years, avg wt.: 185 lb.) and 13 neuropathic, diabetic patients (8 M, 5 F, 61.6 ± 14 years, 212 lb.) in accordance with an IRB-approved protocol. Data related to duration of diabetes, foot size and medical history were collected from each participant and all neuropathy scores for the test group were provided by the referring physician. Each subject walked barefoot on a 3.0 m $\times$ 0.6 m platform which contained a custom built shear and pressure system with a reusable $40 \times 58 \times 0.17$ cm^3 surface stress film (S3F) sensitive to pressure and shear (Stucke et al., 2012). All participants took one step on the platform striking the evenly-leveled sensor platform with the second step and completed the gait cycle on the opposing side of the sensor platform. Six to eight steps were recorded for each subject and all subjects were instructed to look ahead so as to avoid irregular gait. The measured foot varied between subjects; however, it stayed consistent among each participant. For this study, posterior or anterior shear refers to the forces experienced by the sensor platform. For instance, at heelstrike, the sensors would detect an anterior shear force under the heel.

Four of the total steps for each participant were analyzed chosen by documented observation of the utmost natural occurring and a Matlab script was utilized for determination of plantar pressure and shear forces. The script divided the plantar foot into ten regions, 3 of which were the primary focus for the present study due to alignment along the first metatarsal ray: hallux, first metatarsal head (MTH), and lateral heel (Cavanagh and Rodgers, 1987). Peak pressure, peak anterior shear, and peak posterior shear were determined for the three previously mentioned regions for all 116 steps. Each peak force value was then averaged between the four steps. The toe/first MTH load ratios were determined for peak pressure (Ph/Pm) and posterior shear (Sh/Sm). The load ratios for each subject were analyzed using a general linear model ANOVA in Minitab with group (control versus diabetic) as the main factor and stance time and body weight as covariates. These covariates minimize the effects of differences in body weight and walking speed between the two groups. A separate Matlab code was configured to determine peak anterior shear in the MTH region and peak posterior shear in the lateral heel region in the first 50% of stance to ensure measurement of maximum shear difference during total foot contact. During the early instances of toe-off, a large anterior shear force will be present under the 1st MTH and could potentially shadow the measurement of interest hence the first 50% of stance being chosen for analysis. The peak posterior shear on the lateral side of the heel region was subtracted from the 1st MTH peak anterior shear to create a variable "$S_{flatten}$" that was compared between control and diabetic subjects using a *t*-test. The subtraction of the two shear forces eliminated the effect of velocity during gait and thereby provided insight into the mechanics of arch support during gait.

3. Results

The peak pressure load ratio (Ph/Pm) averaged 2.10 ± 1.08 among the control subjects and 1.13 ± 0.74 among the neuropathic, diabetic subjects, $p = 0.03$ (Fig. 1 and 2). The posterior shear load ratio (Sh/Sm) was similarly significantly higher for control subjects (1.87 ± 0.88) than for diabetic patients (0.88 ± 0.45), $p = 0.004$ (Fig. 3).

A two-sided *t*-test analyzed the difference in peak anterior shear from the MTH region to the peak posterior shear from the lateral heel region at $< 50\%$ stance time. The diabetic group displayed a significantly higher kPa difference in the two shears with a generated *p*-value $= 0.002$ (Fig. 4).

The neuropathic diabetic group had a significantly higher $S_{flatten}$ value than the control group ($p = 0.002$). However, the fact that Arch Indices (Cavanagh and Rodgers, 1987) were similar for the two groups ($p = 0.539$) indicates that the diminished muscular support of the longitudinal arch in the diabetic group had not yet manifested itself in a "collapsed" foot structure.

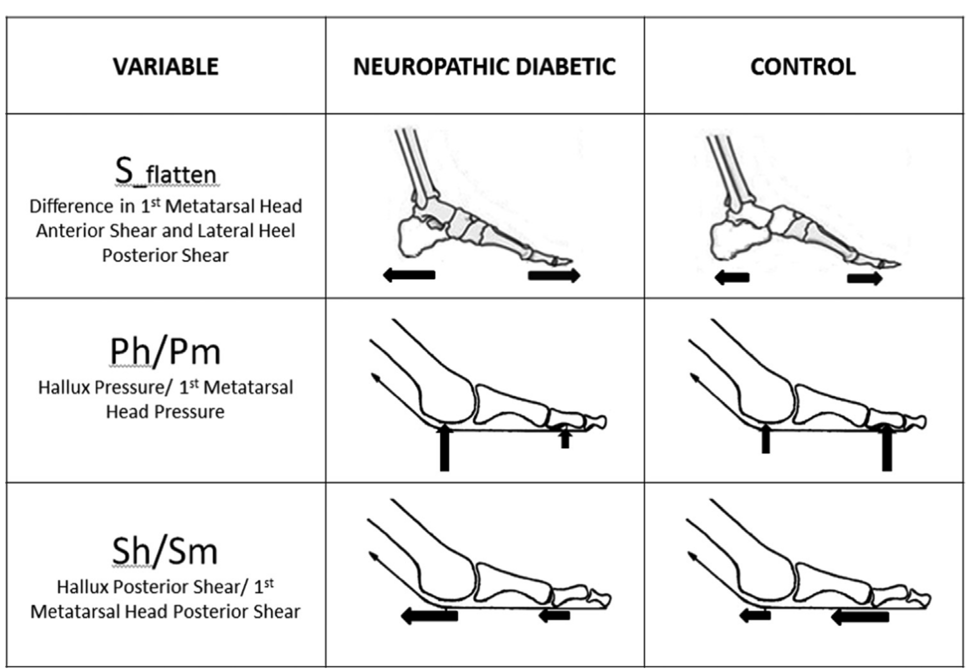

Fig. 1. Hypothesized Shear and Pressure in the 1st Metatarsal Ray. Variable "S_flatten" refers to a measure of shear stresses associated with an arch that is collapsing, "Ph/Pm is the ratio of pressure measurements under the hallux and fist metatarsal head, and "Sh/Sm" refers to a similar ratio for antero/posterior shear forces.

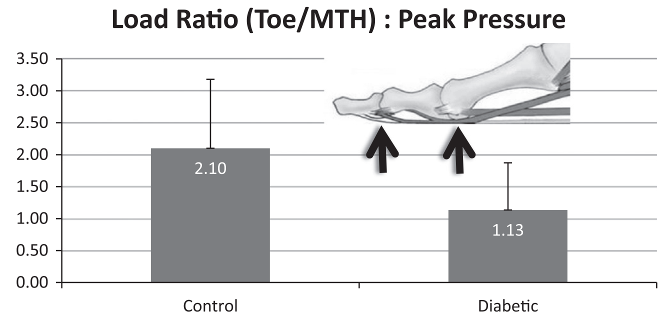

Fig. 2. Hallux and 1st metatarsal head peak pressure ratios in control and neuropathic diabetic subjects during gait.

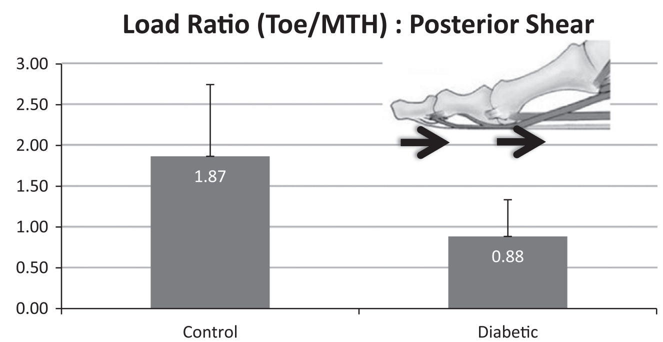

Fig. 3. Hallux and 1st metatarsal head peak posterior shear force ratio in control and neuropathic diabetic subjects during gait.

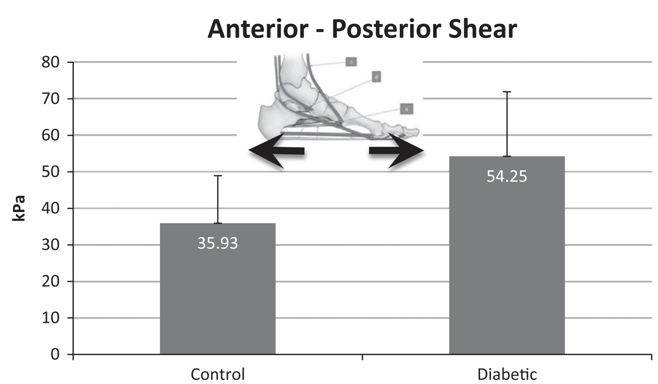

Fig. 4. Difference in 1st metatarsal head anterior shear and lateral heel posterior shear during first half of stance during complete plantar contact (i.e., midstance phase of gait).

4. Discussion

For this study, a novel shear and pressure measurement device was used to assess biomechanical factors associated with arch support. While others have used a combination of video-based and 3D shape models (e.g., generated in PhotoModeler Scanner (Alshadli et al., 2013)), to quantify foot architecture, our approach was to use a single measurement technique to examine factors responsible for maintaining the longitudinal arch. As hypothesized, the intrinsic muscles and/or flexor muscles of the foot show reduced ability in diabetic patients, as measured by the interactions between the hallux and the support surface. Both peak pressure and peak shear load ratios (Ph/Pm and Sh/Sm) are significantly reduced in neuropathic diabetic patients – even prior to any overt signs of a flattened longitudinal arch. Corroborating these findings is the fact that $S_{flatten}$ was significantly elevated in the diabetic group.

One limitation with the study is the age gap between control and experimental groups. To the authors' knowledge, there have not been any studies showing differences in arch mechanics between subjects approximately 50 years of age with others who are closer to 60 years. Nevertheless, it is possible that this age gap could have an effect.

In summary, this is the first time (i) dynamic measures of arch support have been quantified in either diabetic or control subjects, (ii) a full analysis of the role of both shear and pressure on arch support has been undertaken, and (iii) changes that potentially predispose a foot to collapse have been identified prior to the foot actually exhibiting an increased arch index. Future work needs to be performed to demonstrate the effects of medial-lateral shear forces and track these patients to ascertain how their arch structure changes over time, given these altered loading conditions.

Conflict of interest statement

The authors have no conflicts of interest with this research project.

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References

Alshadli, D., et al., 2013. Reliability of a high accuracy image-based system for 3D modelling of the medial longitudinal arch during gait, Developments in Multidimensional Spatial Data Models. Springer, New York, pp. 85–101 (ISBN 978-3-642-36378-8).
Birke, J.A., Franks, B.D., Foto, J.G., 1995. First ray joint limitation, pressure, and ulceration of the first metatarsal head in diabetes mellitus. Foot Ankle Int. 16 (5), 277–284.
Cavanagh, P.R., Rodgers, M.M., 1987. Pressure distribution under symptom-free feet during barefoot standing. Foot Ankle Int. 7 (5), 262–278.
Delbridge, L., Perry, P., Marr, S., Arnold, N., Yue, D.K., Turtle, J.R., Reeve, T.S., 1988. Limited joint mobility in the diabetic foot: relationship to neuropathic ulceration. Diabet. Med. 5 (4), 333–337.
Lee, D.G., Davis, B.L., 2009. Assessment of the effects of diabetes on midfoot joint pressures using a robotic gait simulator. Foot Ankle Int. 30 (8), 767–772.
Lord, M., Hosein, R., 2000. A study of in-shoe plantar shear in patients with diabetic neuropathy. Clin. Biomech. 15 (4), 278–283.
Mueller, M.J., Diamond, J.E., Delitto, A., Sinacore, D.R., 1989. Insensitivity, limited joint mobility, and plantar ulcers in patients with diabetes mellitus. Phys. Ther. 69 (6), 453–459.
Mueller, M.J., Sinacore, D.R., Hastings, M.K., Strube, M.J., Johnson, J.E., 2003. Effect of achilles tendon lengthening on neuropathic plantar ulcers* a randomized clinical trial. J. Bone Jt. Surg. 85 (8), 1436–1445.
Stokes, I.A., Hutton, W.C., Stott, J.R., 1979. Forces acting on the metatarsals during normal walking. J. Anat. 129. Pt 3, 579.
Stucke, S., McFarland, D., Goss, L., Fonov, S., McMillan, G.R., Tucker, A., Davis, B.L., 2012. Spatial relationships between shearing stresses and pressure on the plantar skin surface during gait. J. Biomech. 45 (3), 619–622.