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Dynamic plantar loading index detects altered foot function in individuals with rheumatoid arthritis but not changes due to orthotic use

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Abstract

Background: Altered foot function is common in individuals with rheumatoid arthritis. Plantar pressure distributions during gait are regularly assessed in this patient group however the association between frequently reported magnitude-based pressure variables and clinical outcomes has not been clearly established. Recently, a novel approach to the analysis of plantar pressure distributions throughout stance phase, the dynamic plantar loading index, has been proposed. This study aimed to assess the utility of this index for measuring foot function in individuals with rheumatoid arthritis.

Methods: Barefoot plantar pressures during gait were measured in 63 patients with rheumatoid arthritis and 51 matched controls. Additionally, 15 individuals with rheumatoid arthritis had in-shoe plantar pressures measured while walking in standardized footwear for two conditions: shoes-only; and shoes with prescribed custom foot orthoses. The dynamic plantar loading index was determined for all participants and conditions. Patient and control groups were compared for significant differences as were the shod and orthosis conditions.

Findings: The patient group was found to have a mean index of 0.19, significantly lower than the control group's index of 0.32 (p>0.001, 95% CI [0.054, 0.197]). No significant differences were found between the shoe-only and shoe plus orthosis conditions. The loading index was also found to correlate with clinical measures of structural deformity.

Interpretation: The dynamic plantar loading index may be a useful tool for researchers and clinicians looking to objectively assess dynamic foot function in patients with rheumatoid arthritis, however it may be unresponsive to changes caused by orthotic interventions in this patient group.

Keywords: Rheumatoid arthritis; Plantar pressure; Foot; Foot orthoses

Introduction

Rheumatoid arthritis (RA) commonly affects the foot and lower limb, resulting in the hallmark signs and symptoms of pain, stiffness, deformity and functional disability (van der Leeden et al, 2008; Grondal et al, 2008). Despite recent advances in medical treatment options, in many cases the disease remains active in the foot after the patient has been classified as being in remission (Wechalekar et al, 2012; Bakker et al, 2011; van der Leeden et al., 2010). Moreover, recent research has demonstrated that abnormal foot mechanics as well as inflammatory disease factors contribute independently to the overall burden of foot disease (Barn et al, 2013; Hooper et al, 2012; Turner et al, 2008). Conservative treatment options are available, with prescription footwear (Williams et al., 2007; Dahmen et al., 2014) and custom orthotic interventions (Woodburn et al., 2002; Chang et al., 2012; Hennessy et al., 2012) shown to be effective at reducing pain and peak forefoot plantar pressures.

Plantar pressure distributions measured during walking are altered in this patient group (Turner & Woodburn, 2008; Semple et al, 2007). Increased pressures, particularly at the metatarsophalangeal joints (MTPJs) may correlate with pain, however the relationship between pressure, forefoot pathology and ulceration remains unclear (Firth et al., In Press; Bowen et al, 2011; Schmiegel et al., 2008). Most studies reporting plantar pressures in individuals with RA have tended to use discrete, magnitude-based variables to detect abnormal biomechanics and assess interventions, for example peak pressure or pressure time integrals within an anatomically defined region (Bowen et al., 2011; Chang et al., 2012). This analysis strategy may be limited in terms of failing to fully account for changes in the functional behaviour of the foot during gait and by the fact that these variables can be confounded by walking speed, which is often altered in this patient population (Paul et al., 2014). Furthermore, the lack of standardized thresholds and difficultly in interpreting these variables may limit the applicability of magnitude-based analysis (Guldemond et al., 2006).

A novel approach to the analysis of plantar pressure distributions, the dynamic plantar loading index (DPLI) has recently been proposed by Najafi et al (2010). The DPLI is a variable which is derived from pressure measurements taken throughout stance phase rather than at a single instance, and has the added advantage of being independent of walking speed (Najafi et al., 2010). The index has been demonstrated to be effective in identifying abnormal foot function in Charcot neuroarthropathy and furthermore to provide an objective measure of improvements in function after surgery (Najafi et al., 2010). Similarly, its utility has been demonstrated in identifying abnormal foot function in individuals with pes cavus foot type and measuring the effectiveness of an orthotic intervention in terms of altering plantar pressure distributions to within normal limits (Najafi et al., 2012, Najafi et al., In Press).

The aim of this study was to determine DPLIs for a cohort of patients with RA and to compare these to a group of matched controls. The relationship between the DPLI and clinical measures of foot structure, disease impact and disease duration were explored, and finally the responsiveness of the DPLI to changes in function caused by custom foot orthoses in this patient population was assessed.

Methods

Participants

Data were retrieved from GCU data archives and a secondary analysis carried out according to the aims and objectives of this article. Barefoot plantar pressure data for individuals with RA (n=63) and matched controls (n=51) were retrieved from a database made up from previous studies (Turner et al., 2008, Turner & Woodburn., 2008). Clinical measures of structural deformity (Forefoot and Rearfoot Structural Indexes (FSI and RSI; Platto et al., 1991), relaxed calcaneal stance position (RCSP)) and impairment and disability (Foot Impact Scale (FIS; Helliwell et al., 2005)) were also retrieved for this group. In-shoe plantar pressure data in patients (n=15) with RA for shod-only and customized foot orthoses conditions were retrieved from Gibson et al (In Press). This study previously showed significant changes in medial and lateral forefoot peak pressures and midfoot contact area as well as foot kinematics and kinetics when participants walked with orthoses compared to shod. All participants in the patient groups had a confirmed diagnosis of RA based on the American College of Rheumatology criteria (Arnett et al., 1988; Aletaha et al., 2010). Participants provided written, informed consent and ethical approval was obtained prior to data collection. Demographic data for all groups are provided in Table 1.

Protocol

For the barefoot trials, participants walked over an Emed pressure measurement platform (Novel GmbH, Munich, Germany) using a two step protocol at a self selected walking speed. Plantar pressures were obtained for the most affected foot only. The plate had a resolution of 4 sensors per cm^2 and data were recorded at 100Hz.

For the shod/orthoses trials, participants had custom orthoses prescribed based on instrument gait analysis and 3D scans of foot shape (Gibson et al., In Press). Devices were manufactured in Nylon 12 via selective laser sintering and fitted by a UK Health and Care Professions Council registered podiatrist. After wearing the orthoses for at least one week prior to testing, participants underwent instrumented gait analysis for shoe-only and orthoses conditions while wearing standardised footwear. The Pedar in-shoe system (Novel GmbH, Munich, Germany) was used to measure plantar pressure distributions at 50Hz for both feet. The order of the test conditions was randomized and participants walked at a self selected speed that was controlled between conditions over flat ground in a straight line.

Data analysis

All data analysis was performed using R (version 3.0.2). Figures were produced using the ggplot2 package (Wickham, 2009). The process for determining the DPLI has been described in detail elsewhere (Najafi et al., 2010, Najafi et al., 2012). Briefly, the peak plantar pressure at 101 points across stance phase was determined. This dataset was split into a frequency histogram of 30 evenly spaced bins describing the pressure distribution, and this is then compared to a matched Gaussian distribution with the same mean and variance as the original pressure data. The regression factor of the comparison is the DPLI. The code used to determine the DPLI from the plantar pressure data has been included as a supplementary file to this article.

The mean of five trials was used for the barefoot analysis and the mean of twelve steps used for the in-shoe analysis. DPLI between patient and control groups were compared using the appropriate t-test or non parametric equivalent as were the orthotic and shoe-only conditions (α=0.05). Additionally, to assess the DPLI's sensitivity to the input parameters of the technique, repeat analyses of the barefoot data were performed with the number of bins set to 10, 15, 20, 25, 35 and 40. The Pearson product-moment correlation coefficient was determined to assess the relationship between the DPLI and each of the clinical measures described earlier (FSI, RSI, RCSP, FIS) and disease duration). The standardised response mean (SRM), defined as the mean difference between the shod and orthotic conditions divided by the standard deviation of the differences between the paired measurements, was computed for the DPLI along with standard variables of peak pressure and contact area to assess responsiveness.

Results

Results for the comparison between RA and control groups are presented in Figure 1. The RA group was found to have a mean DPLI of 0.19 which was significantly lower than the control group's index of 0.32 (p>0.001, 95% CI [0.054, 0.197]; independent, two sample t-test). Representative histograms of pressure distributions for both groups are presented in Figures 2 and 3. Decreasing the number of bins used in the analysis below 25, the DPLI for both groups tended to increase, however from 25-40 bins the results were relatively stable (varying by <4% from the mean for this subset of bins). In all cases the main findings were not significantly affected. The full results from the bin sensitivity analysis have been included as supplementary materials.

The DPLI was found to be significantly correlated with both the FSI (p=0.0019, r^2=0.1511) and the RCSP (p=0.0018, r^2=0.1501). Scatterplots for both are presented in Figure 4. No significant correlation was found between DPLI and disease duration (p=0.4352), RSI (p=0.8451) or FIS (p=0.6747). Results for the comparison between DPLIs with shoes-only and shoes plus orthoses are presented in Figure 1. No statistically significant differences were found between conditions (p=0.903, 95% CI [-0.06, 0.063]; repeated measures t-test). The SRM for the DPLI when assessing orthotic interventions was 0.012, compared to 3.4 and 3.3 for peak and lateral forefoot pressures respectively and 10.4 for midfoot contact area.

Discussion

The DPLI has previously been demonstrated to be a useful variable for measuring altered foot function in patients with Charcot neuropathy and pes cavus foot type. This study extends its utility to patients with inflammatory joint disease, with the lower DPLI score in the RA group indicative of altered plantar loading during gait. The advantages of the DPLI - walking speed independence and the provision of a single, dynamic measure of foot function rather than peak pressure values at discrete time points – suggest it may have some clinical utility as a screening or monitoring tool that is complimentary to more commonly reported magnitude-based measures.

Limitations of magnitude-based plantar pressure measurements in patients with rheumatoid arthritis have been identified. It has been demonstrated that peak plantar pressures are not significant predictors of increased ulceration risk, with research suggesting a more complex pathway to ulcer development, including loss of protective sensation and deformity (Firth et al., In Press). However, inter-subject variability in gait, including the disease's known influence on walking speed, may confound peak pressure measurements at regions of interest.

The DPLI was found to be significantly correlated with two measures of structural deformity (FSI and RCSP). This suggests that the presence of a foot deformity may be an importance contributory factor in deviations from a "normal" plantar pressure distribution as measured by the DPLI. This is in line with previous findings that static measures of foot deformity can be related to abnormal pressure parameters (Mootanah et al., 2013). The lack of a correlation with the FIS may result from the fact that this scale covers all aspects of foot related disability including personal factors and footwear. No significant relationship to disease duration was found at the group level, however further studies may investigate whether DPLI can provide a proxy indicator for changes in foot function over time on an individual basis.

Findings from studies using the DPLI suggest that healthy individuals with normal foot function will have a spatiotemporal pressure distribution closer to a matched Gaussian distribution than those with abnormal function as a result of disease or deformity. It is unclear however whether a hypothetical ideally functioning foot and gait pattern would produce a DPLI of 1 (i.e. a normally distributed pressure pattern over stance phase). DPLI results from previous studies for young healthy subjects who would be expected to have excellent foot function were found to be around 0.45 (Najafi et al., 2010) and 0.51 (Najafi et al., 2012), suggesting that this may not be the case. These results are higher than the index found for the control group in the present study, possibly as a result of the older control group in the present study (mean 55 years compared to ~25 years in the previous studies), since increasing age is a factor which has been demonstrated to affect plantar pressures (Scott et al., 2007).

Previous research has shown that foot orthoses can produce a DPLI more in line with those of control participants in individuals with pes cavus foot type (Najafi et al., 2012). In patients with RA affecting the foot, custom foot orthoses are a recommended intervention (Hennessy et al., 2012). Therefore it was hypothesized that the DPLI could provide an additional biomechanical target that may assist in the designing functionally optimised foot orthoses (Gibson et al., In Press). Analysis of the shoes only vs shoes and orthoses dataset using standard approaches showed significant reductions in peak pressures of 21.9 and 13.9kPa at the medial and lateral forefoot respectively with orthoses, along with significant increases in midfoot contact area (9.4cm^2). However, the results from the current study found no differences between DPLI measured with or without orthoses and a low SRM, suggesting the variable may not be responsive to orthotic interventions in this patient group. The RA foot tends to be flat with a low medial longitudinal arch and valgus hindfoot (Bal et al, 2006; Turner et al, 2003; Shi et al, 2000; Michelson et al, 1994; Bouysset et al, 1987), rather than cavus as in Najafi et al (2012) and this may be one of the reasons for the lack of change in DPLI through orthotic use in this patient group.

The effect of wearing comfortable training shoes alone may improve plantar pressure loading characteristics. Hennessy et al (2007) conducted a single-blind cross-over trial of three footwear conditions, and found that commercially available premium cushioned running shoes were most effective in reducing plantar pressures relative to orthopaedic footwear and a control shoe. Similar findings have been demonstrated in a trial of orthopaedic footwear plus cushioned insoles versus orthopaedic footwear plus custom-made foot orthoses, where both groups experienced similar levels of foot pain relief (Cho et al, 2009). The mean DPLI measured for the shod condition was higher than that measured barefoot (0.4 vs 0.19) for individuals with RA, therefore use of comfortable training shoes as the vehicle for orthoses may partially explain the similar DPLI values in this part of the analysis.

We demonstrated in this study that the absolute value of the DPLI generated can be sensitive to its input parameters, i.e. the number of bins used. For the current study we based our primary reporting of the results on the 30 bin value as in Najafi et al (2012). Our analysis showed little variation between results for analyses using bin numbers from 25-40 and recommend future work using the DPLI should continue to be based around 30 bins for the analysis to allow direct comparison between studies.

Several limitations with the present study should be noted. We utilised both platform and in-shoe pressure measurement systems. The platform pressure measurement system has approximately four times greater resolution than the in-shoe system, and the disadvantages of in-shoe vs platform plantar pressure measurement systems are well described (Orlin & McPoil, 2000). However previous research on cavus foot type found the performance of the in-shoe system to be adequate to determine changes in the DPLI (Najafi et al., 2012) and their ability to accurately determine temporal and force variables have been established (Barnett et al., 2001). Additionally, the patients used for the orthosis analysis were less than two years from diagnosis. It is possible that those with longer disease duration may show different results.

The DPLI may be a useful tool for researchers and clinicians looking to objectively assess dynamic foot function in patients with RA, however it may be unresponsive to changes caused by orthotic interventions in this group. Further work is required to determine if the DPLI provides additional clinically relevant information beyond more commonly used measures of plantar pressure.

Conflict of interest

The authors report no conflict of interest.

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Figure legends

Figure 1 – Dynamic plantar loading indexes for Control and RA groups (left) and shod and orthotic conditions (right). DPLI: dynamic plantar loading index; Orth=orthotic group; ***=$p<0.001$

Figure 2 – Histogram with Gaussian distribution line overlaid (left) and contour plot (right) of pressure distribution for RA participant. DPLI: dynamic plantar loading index

Figure 3 – Histogram with Gaussian distribution line overlaid (left) and contour plot (right) of pressure distribution for control participant. DPLI: dynamic plantar loading index

Figure 4 – Scatterplots for Dynamic Plantar Loading Index (DPLI) vs Forefoot Structural Index (left); and Dynamic Plantar Loading Index vs Relaxed Calcaneal Stance Position (right). Shaded areas represent 95% confidence region. DPLI: Dynamic Plantar Loading Index; FSI: Forefoot Structural Index; RCSP: Relaxed Calcaneal Stance Position.

Tables

Table 1. Demographic data for RA cases and control subjects

Demographic characteristic	**RA barefoot (n=63)**	**RA orthotic (n=15)**	**Control (n=51)**
Age (years)*	57 (12.3)	50.7 (8.7)	55 (11.6)
Gender (F:M)	49:14	11:4	37:18
Body mass index*	26 (4.7)	27.5 (4.5)	26 (4.4)
Disease duration (years)*	13.6 (11.9)	0.8 (range 0.25-1.9)	-

*Mean (standard deviation); F:M, female to male gender ratio

Figures

Figure 1

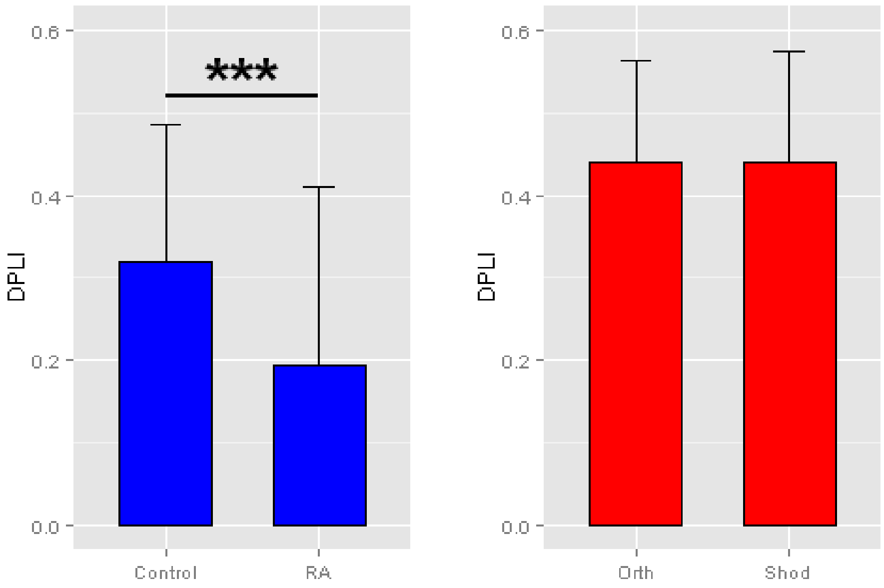


Figure 2

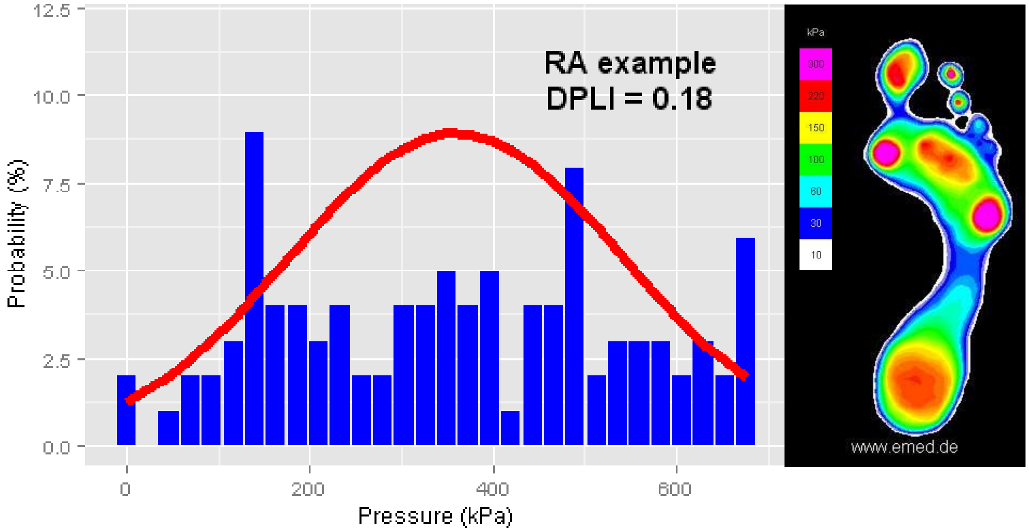

RA example
DPLI = 0.18
Probability (%)
12.5
10.0
7.5
5.0
2.5
0.0
0
200
400
600
Pressure (kPa)
kPa
300
220
150
100
60
30
10
www.emed.de

Figure 3

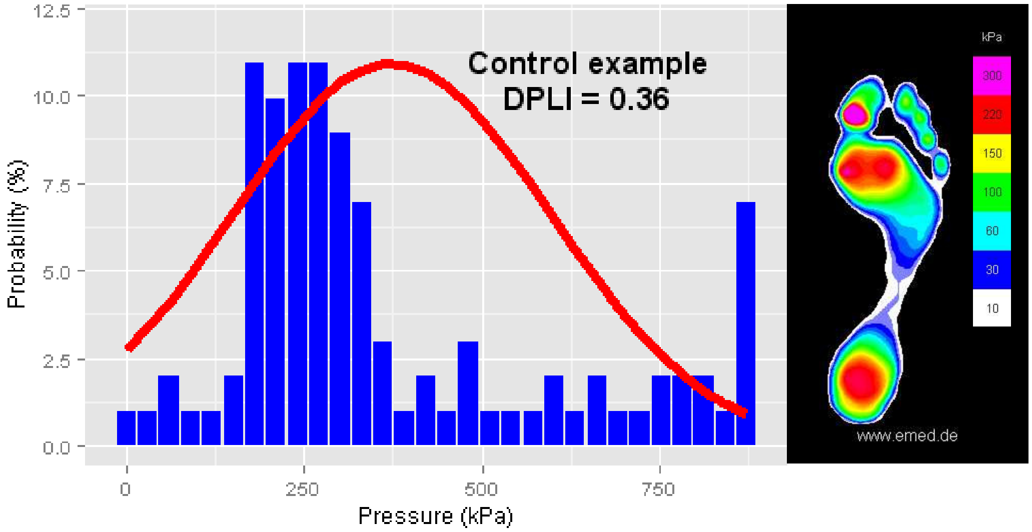
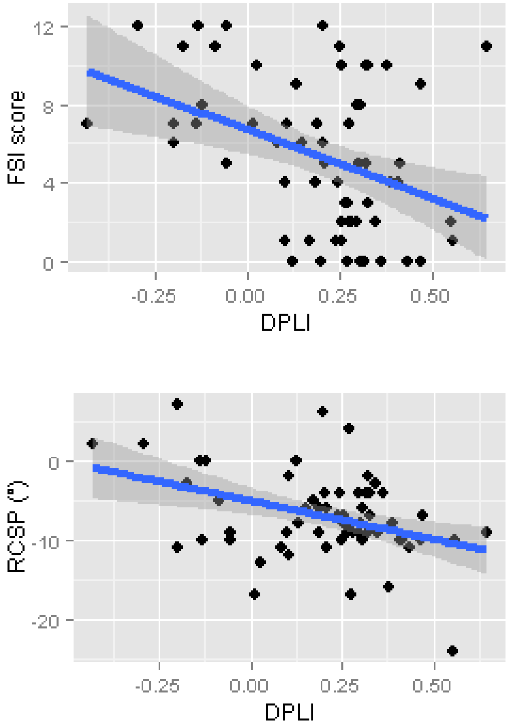

Control example
DPLI = 0.36
Probability (%)
12.5
10.0
7.5
5.0
2.5
0.0
0
250
500
750
Pressure (kPa)
kPa
300
220
150
100
60
30
10
www.emed.de

Figure 4


FSI score
12
8
4
0
-0.25
0.00
0.25
0.50
DPLI
RCSP (°)
0
-10
-20
-0.25
0.00
0.25
0.50
DPLI