The influence of population characteristics and measurement system on barefoot plantar pressures: A systematic review and meta-regression analysis

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ARTICLE INFO

ABSTRACT

Background: The measurement of plantar pressure distributions during gait can provide insights into the effects of musculoskeletal disease on foot function. A range of hardware, software, and protocols are available for the collection of this type of data, with sometimes disparate and conflicting results reported between individual studies. In this systematic review and meta-regression analysis of dynamic regional peak pressures, we aimed to test if 1) the system used to obtain the pressure measurements and 2) the characteristics of the study populations had a significant effect on the results.

Methods: A systematic review of the literature was undertaken to identify articles reporting regional peak plantar pressures during barefoot walking. A mixed-effects modeling approach was used to analyze the extracted data. Initially, the effect of the system used to collect the data was tested. Following this, the effect of participant characteristics on the results were analyzed, using moderators of cohort type (defined as the primary health characteristic of the participants), age, sex, and BMI.

Results: 115 participant groups were included in the analysis. Sufficient cohorts were available to test those that consisted of healthy individuals, and those with diabetes and diabetic neuropathy. Significant differences were found between results reported by studies using different pressure measurement systems in 8 of the 16 regions analyzed. The analysis of participant characteristics revealed a number of significant relationships between regional peak pressures and participant characteristics, including: BMI and midfoot plantar pressures; elevated forefoot pressures as a result of diabetic neuropathy; and sex-differences in regional loading patterns.

Conclusions: At the level of the literature, we confirmed significant effects of disease status, age, BMI, and sex on regional peak plantar pressures. Researchers and clinicians should be aware that measurements of peak plantar pressure variables obtained from different collection equipment are not directly comparable.

1. Introduction

For researchers and clinicians, the measurement of plantar pressure distributions to characterize the mechanical interaction between the foot and ground during walking has become an important tool for the assessment of pathological conditions [1,2] as well as for the prescription and design of interventions intended to treat these problems [3,4]. Significant correlations have been shown to exist between variables drawn from pressure data and clinical outcomes such as pain and tissue damage [5], allowing objective screening criteria and treatment targets to be derived [6,7]. In comparison to many other forms of biomechanical data measured during gait, the collection of plantar pressures is relatively fast and efficient, making it potentially easy to translate into clinical practice.

There are many factors that can directly or indirectly influence plantar pressure distributions. For example, there are several commercially available pressure measurement platforms available, each utilizing different sensing technologies and different technical specifications (e.g. measurement frequency, sensor size) [8]. The characteristics of the study population has also been shown to have a significant effect, with factors including disease status [9], age [10], and body mass index (BMI) [11] all having been suggested to correlate with plantar loading patterns. Across the literature, varying and sometimes conflicting results have been reported, for example with presented results for peak pressures below the forefoot in individuals with diabetic neuropathy ranging from > 800 kPa [12,13] to somewhere around half that value [14,15], and inconsistent reports as to the regions of the foot that are affected by the disease [14,16,17].

Assessing which factors are consistently supported may have implications for study design and the interpretation of plantar pressure-

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based results. In this systematic review and meta-regression analysis, our objective was to assess, at the level of the literature, factors that may influence peak regional plantar pressure measurements and to characterize their effect. We hypothesized that for regional barefoot peak pressures, 1) different measurement systems have reported significantly different results, and 2) study population characteristics including disease, age, BMI, and sex have a significant influence on the results.

2. Methods

2.1. Search strategy

The PubMed and Web of Science databases were searched for titles and abstracts that contained the terms "plantar pressure" or "pedobarography", along with related Medical Subject Headings (MeSH). The primary search was carried out on 2018/07/27. Reference lists were also reviewed, and any additional relevant literature identified.

2.2. Selection criteria

Original English language research studies from the earliest available date that reported regional peak pressures during barefoot walking were considered for inclusion. Studies using matrix style sensing arrays were eligible for this analysis, therefore studies using discrete sensors that were attached below specific regions of the foot were excluded. Studies reporting on interventions were included if they reported baseline plantar pressure measurements. Only studies that presented results for adult participants (defined as > 18 years) were included due to the potential for confounding effects from the developing foot [18]. To avoid duplication of results, we attempted to identify any studies that were re-analyses of previously reported experiments and excluded these papers as required. For all search results, titles and abstracts were reviewed by the authors to determine if they met the inclusion criteria, and full texts inspected if insufficient information was presented in the abstract.

2.3. Methodological quality

A quality index that has previously been utilized for literature reviews based around cross sectional studies of biomechanical factors was used to rate the quality of the articles [19–21]. Two reviewers (ST and JB) performed the assessment and any discordant results were resolved by consensus discussion. Articles scoring less than 50% on the quality score were excluded from the main analysis.

2.4. Data synthesis

The reviewers performed a data extraction process on qualifying papers. For each cohort included in the review, demographic details were identified and extracted, including the proportion of each sex making up the sample, and the average height, weight, and BMI of the study population. The primary health-related characteristic reported by the paper for each test group (for example: diabetes, rheumatoid arthritis, healthy control) was noted, and is henceforth referred to as cohort type. Any additional information related to the cohort type (for example: neuropathy as an additional complication of diabetes) was recorded in a separate category. The measurement system used to collect the data was identified, with the particular model used recorded when available.

Measurement data associated with peak regional plantar pressures were identified and extracted. As far as possible, we attempted to confirm that studies reporting peak pressures used the definition: *the highest pressure recorded by an individual sensor within the region of interest during the measurement, averaged over a number of trials.* There are a large number of variables that can be drawn from plantar pressure data, for

example: contact times, pressure time integrals, and forces. However, based on the papers identified during the search, regional peak pressures remain the most commonly reported. Therefore, the presented analysis was based around this measurement. The plantar regions that we included in the analysis were those associated with the hindfoot: complete hindfoot, medial hindfoot, lateral hindfoot; the midfoot: complete midfoot, medial midfoot, lateral midfoot; forefoot: complete forefoot, medial forefoot, central forefoot, lateral forefoot, distal metatarsal heads 1–5; and the hallux and lesser toes. Where necessary, the units of extracted data were converted to kPa to allow comparison across all studies. In cases where results were presented graphically, relevant data points were electronically digitized from the figure(s) given in the published paper. When a study involved a repeated measures analysis to assess the effects of an intervention, we used the control condition, generally considered to be the participant's baseline walk without the intervention.

2.5. Statistical analysis

All analysis was carried out using the metafor package [22] on R V3.4.3. The complete analysis code and extracted data can be found at https://github.com/Telfer/PP_MetaRegression. A mixed effects meta-regression of summary statistics was used to test the data. In all cases, we required there to be at least 10 cohorts available for each statistical model. This was based on recommendations from the Cochrane Handbook [23]. For hypothesis 1, we restricted the included cohorts to healthy subjects as this cohort included the largest number of participants, and to pressure platforms used by at least 10 studies that reported relevant regional peak pressure results. To determine if there was a significant effect due to the system, a chi-squared test was performed, followed by pairwise tests to compare pressure measurement systems. Based on the results of testing hypothesis 1, the analysis for hypothesis 2 was performed independently for each of the measurement systems. Moderator variables of cohort type (the primary health characteristic of each group), age, percentage of the cohort that was female, and body mass index were included in the model. These variables were chosen as they have previously been suggested to influence plantar loading [11,24], and were generally well reported in the majority of articles included in this review. If an insufficient number of cohorts was available for a particular system, the dataset for that system was restricted to the cohort type reported in the largest number of studies, and the cohort type moderator not included in the mixed effects model. As before, a chi-squared test was used to test for overall significance, followed by moderator specific pairwise tests. The threshold for statistical significance was set at α = 0.01 to account for multiple comparisons.

3. Results

3.1. Measurement systems

In total, after removal of duplicates, the literature search initially identified 1598 articles, of which 234 met the inclusion criteria after initial screening (Fig. 1). Reviews of full texts for suitability, including quality assessment, led to a further 40 being excluded, leaving 194 that met the inclusion criteria of the study. After restricting the included papers to those that used a pressure platform that was used in at least 10 studies and a health condition reported in at least 10 studies, 82 papers (125 cohorts) were included in the analyses (Table 1). Quality assessment results for the included papers and complete results from each statistical model are provided in the supplementary materials.

The analysis for hypothesis 1, the effect of measurement system, included 93 cohorts of healthy subjects, representing 6717 individuals. Three systems were sufficiently represented in the literature to be included. These were: the emed SF4 (Novel GmbH, Munich, Germany), 59 cohorts; footscan (RSScan, Paal, Belgium), 17 cohorts; and MatScan
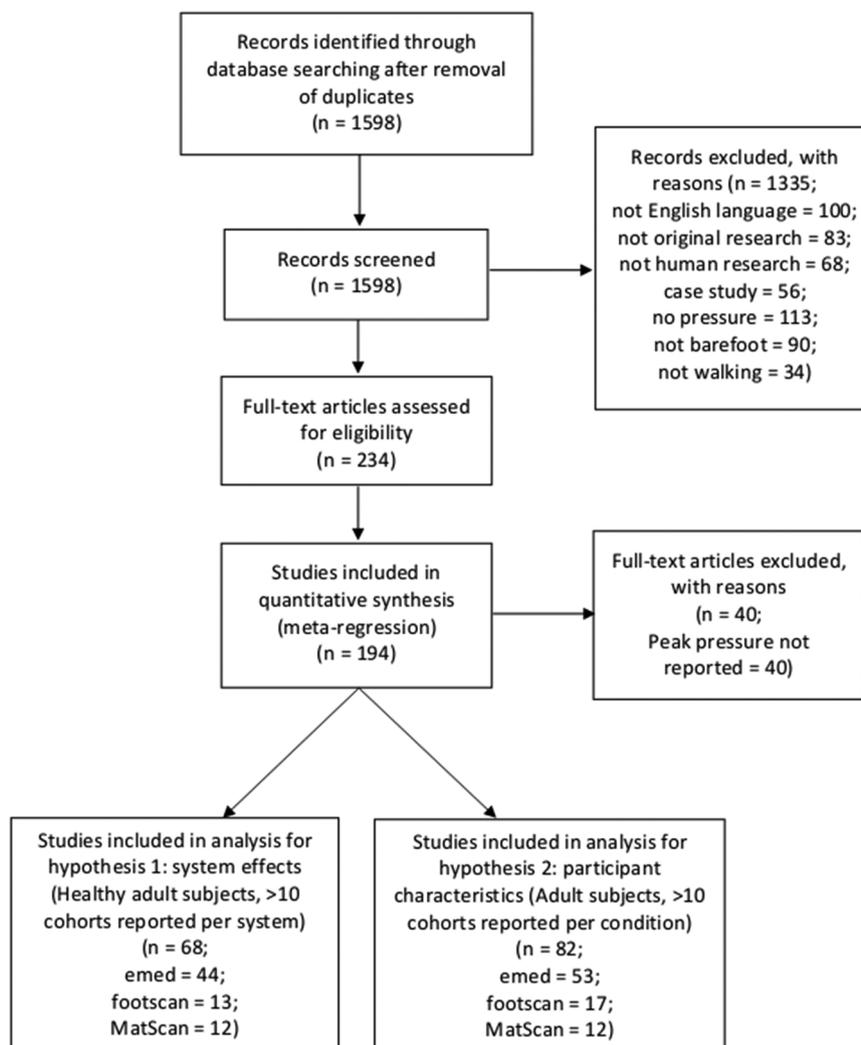
Fig. 1. Flow of studies. An initial 1598 articles were identified, and subsequently reduced to 194 after screening of abstracts and review of full texts.

(TekScan Inc, Boston, MA), 17 cohorts. The analysis revealed a significant effect of system on the reported pressure measurements for 8 of the 16 regions assessed (Fig. 2). The emed and footscan systems differed at the hallux, metatarsals 1, 3, 4, 5, and midfoot, with studies using the footscan system tending to report lower peak pressure values. The MatScan and footscan systems differed at the hallux, lesser toes, forefoot, metatarsal head 5, and the midfoot regions. The emed and MatScan systems differed at the forefoot and lesser toe regions.

Due to the significant differences between measurements recorded using different systems, for the analysis of participant characteristics the meta dataset was performed individually for each of the systems tested for hypothesis 1. Sufficient data was reported by the included studies to analyze cohorts of healthy individuals, those with diabetes, and those with diabetic neuropathy for both the emed (81 cohorts, 2789 individuals), and footscan (27 cohorts, 972 individuals) systems, along with the age, BMI, and sex moderator variables. Due to the small number of reported cohorts with diabetes and diabetic neuropathy for the MatScan system, the model here was restricted to the age, BMI and sex moderator variables (17 cohorts, 4271 individuals).

3.2. Diabetes and neuropathy

Several significant effects associated with primary health characteristics of the study cohorts were found. Detailed results are presented in Table 2. These were not consistent between systems. The footscan meta-data showed significant differences below the midfoot

when comparing those with diabetic neuropathy and healthy individuals (equivalent to a 249 kPa increase with neuropathy). In the emed meta-data however, no differences were seen at the midfoot for cohort type. The emed meta-data did show that diabetic neuropathy was associated with increases in peak pressures below metatarsal heads 1 and 4 when compared both to healthy individuals (by an average of 92 kPa and 34 kPa respectively) and, in the case of metatarsal head 1, individuals with non-neuropathic diabetes (by an average of 111 kPa). In addition, peak pressures below the hindfoot were increased by an average of 81 kPa in the neuropathic populations compared to healthy groups. There were no significant differences found between cohorts of individuals with diabetes and healthy cohorts for either system.

3.3. Demographics

For both the footscan and emed meta-datasets, BMI was found to be positively associated with increasing peak pressure below the midfoot regions. These results suggest that for every unit increase in BMI, an increase of between 5 and 27 kPa is seen at the midfoot regions. BMI was also found to be positively associated with increases in peak pressures below metatarsals 1 and 4, the hallux and the lesser toes (average increase of 39, 3.3, 61, and 26 kPa per unit of BMI respectively). Age was positively associated with elevated pressures below the medial midfoot and 1 st metatarsal head (Fig. 2) in the emed meta-data, with the model suggesting a decrease of −1 kPa per year and an increase of 2 kPa per year for each region respectively. The footscan meta-

Table 1
Details of the studies included in the analysis. The full list of studies is provided in the supplementary materials.

Author, Year, (ref)	Cohort(s)	System	N
Keklicek, 2018 [40]	Healthy	footscan	20
Fryzowicz, 2018 [41]	Healthy	footscan	28
Walsh, 2017 [31]	Healthy	MatScan	68
Xu, 2017 [42]	Healthy	footscan	32
Cetin 2017 [43]	Healthy	emed	40
Neri, 2017 [44]	Healthy	emed	62, 88, 61
Kanchanasamut, 2017 [45]	Neuropathy	footscan	11, 10
Merriweather, 2016 [46]	Diabetes	emed	28
Said, 2016 [47]	Healthy	footscan	19, 15, 16
Stevens, 2017 [48]	Healthy	footscan	12
Wilkins 2016 [49]	Healthy	emed	12
Couppe, 2016 [50]	Diabetes	emed	10
Cerrahoglu, 2016 [51]	Diabetes, Neuropathy	footscan	38, 38
Mickle, 2015 [52]	Healthy	emed	128, 79, 105
Lu, 2015 [53]	Healthy, Neuropathy	emed	6, 6
Sullivan, 2015 [54]	Healthy	emed	70
Aydin, 2015 [55]	Healthy	footscan	33
Fishco, 2015 [56]	Healthy	emed	28
Barn, 2015 [12]	Neuropathy	emed	167
Shakibi, 2015 [57]	Healthy	emed	32, 28
Hagen, 2015 [58]	Healthy	emed	10, 10
Song, 2015 [59]	Healthy	emed	21, 20
Qiu, 2015 [60]	Diabetes	footscan	65
Shibuya, 2014 [61]	Healthy	footscan	12
Turner, 2014 [62]	Healthy	emed	22
Zhang, 2014 [63]	Neuropathy	footscan	30, 30
Galica, 2013 [64]	Healthy	MatScan	3707
Robinson, 2013 [9]	Healthy, Diabetes	emed	30, 28
Scalpello, 2013 [65]	Healthy	MatScan	10
Melai, 2013 [66]	Healthy, Diabetes, Neuropathy	emed	19, 39, 94
Rosenbaum, 2013 [67]	Healthy	emed	12
Escamilla-Martinez, 2013 [68]	Healthy	footscan	30
Hafer, 2013 [26]	Healthy	MatScan, emed	22
Schuh, 2013 [69]	Healthy	emed	14
Hillstrom, 2013 [70]	Healthy	emed	27, 22, 12
Menz, 2013 [71]	Healthy	MatScan	75
Frigg, 2012 [72]	Healthy	emed	35
Gurney, 2013 [73]	Neuropathy	emed	10
Naemi, 2012 [74]	Healthy	footscan	21
Chung, 2012 [75]	Healthy	footscan	15, 15
Mickle, 2011 [29]	Healthy	emed	71, 36
Allet, 2011 [76]	Healthy	emed	18
Pataky, 2011 [77]	Healthy	emed	104
Kaipel, 2011 [78]	Healthy	emed	45
Zammit, 2010 [79]	Healthy	MatScan	30
Jung, 2011 [80]	Healthy	MatScan	5, 8, 7, 7
Han, 2011 [81]	Healthy	MatScan	10, 9
Monteiro, 2010 [82]	Healthy	footscan	61, 60
Hetsroni, 2010 [83]	Healthy	emed	10
Chevalier, 2010 [84]	Healthy	MatScan	21
Owings, 2009 [6]	Neuropathy	emed	49
D'Aout, 2010 [85]	Healthy	footscan	16
Salekzamani, 2009 [86]	Healthy	emed	10
Bosch, 2009 [87]	Healthy	emed	26, 26
Savelberg, 2009 [17]	Healthy, Diabetes, Neuropathy	emed	10, 8, 10
Diezi, 2008 [88]	Healthy	emed	29
Gurney, 2009 [89]	Healthy	emed	7, 9, 12
Guldemond, 2008 [16]	Diabetes, Neuropathy	emed	49, 44
Walters, 2008 [90]	Healthy	emed	32
Mueller, 2008 [91]	Healthy, Neuropathy	emed	12, 12
Zammit, 2008 [92]	Healthy	MatScan	20
Turner, 2008 [93]	Healthy	emed	53
Solano, 2008 [94]	Healthy, Neuropathy	emed	41, 33, 35, 44
Scott, 2007 [95]	Healthy	MatScan	50, 50
Orendurff, 2006 [96]	Diabetes	emed	27

Table 1 (*continued*)

Author, Year, (ref)	Cohort(s)	System	N
Giacomozzi, 2006 [97]	Healthy	emed	21
Menz, 2006 [98]	Healthy	MatScan	172
Bus, 2005 [38]	Neuropathy	emed	14
Burns, 2005 [99]	Healthy	emed	30
Birtane, 2004 [100]	Healthy	emed	25, 25
Tuna, 2005 [101]	Healthy	emed	50
Lange, 2004 [102]	Healthy	emed	60
Maluf, 2004 [103]	Neuropathy	emed	14, 14
Taylor, 2004 [104]	Healthy	emed	15
Bryant, 2004 [105]	Healthy	emed	23
Mueller, 2003 [106]	Neuropathy	emed	33, 31
Viswanathan, 2003 [107]	Healthy, Diabetes, Neuropathy	footscan	50, 100, 110, 85
Turner, 2003 [108]	Healthy	emed	23
Eils, 2002 [109]	Healthy	emed	40
Russo, 2001 [110]	Healthy	emed	40
Bryant, 2000 [111]	Healthy	emed	30

data suggested that increasing age is associated with a decrease in peak pressures at the hallux and lesser toe regions. No effect of sex was seen in the footscan meta-data, however for the emed meta-data every percentage point increase in females comprising the study cohort was associated with an increase in peak pressure below the hindfoot (Fig. 2) and metatarsal head 2, and a decrease at the medial midfoot.

For the MatScan system dataset, there were no significant associations found for any of the moderator variables (Fig. 3).

4. Discussion

This review presents a systematic investigation at the level of the literature of methodological and participant characteristic factors that may influence regional peak plantar pressure measurements. Given the increasing clinical utilization of plantar pressure measurement systems and the data they provide, our findings suggest that greater attention to these factors when designing studies and using them for clinical decision making may be required.

We found significant differences between results reported by different systems. These differences did not appear to be systematic across regions or between the analyzed systems. This has several implications for the clinical and research use of pressure measurement platforms. The use of target thresholds, for example those used to define the inclusion of people at-risk of plantar ulceration in intervention studies [25], are likely not generalizable and may need to be specific to the measurement equipment used. Researchers conducting systematic reviews that include the analysis of plantar pressure measurements for specific health conditions should be aware of the differences between systems when attempting to perform meta-analyses of these data, as should individual studies that utilize datasets that combine measurements obtained using different systems. Care should also be taken when making direct comparisons of results from individual studies that used different data collection equipment. It should be noted that this review was restricted to peak regional pressures, and it may be the case that for other variables derived from pressure measurements, for example contact areas or center of pressure, the results from different systems may show better reproducibility, or at least any differences may be acceptable. Previous work comparing the emed and MatScan systems [26] reported "encouraging" reliability results between systems, however intraclass correlation coefficients for measurement systems from the same manufacturer were below 0.7 for 25 of the 56 variables tested. In the current analysis the emed and MatScan systems were the most in agreement, only differing at two of the regions tested.

The relationship between diabetic neuropathy and elevated plantar pressures has been well described, particularly in the context of diabetic foot ulcer risk [1]. Our findings support this link, demonstrating a large
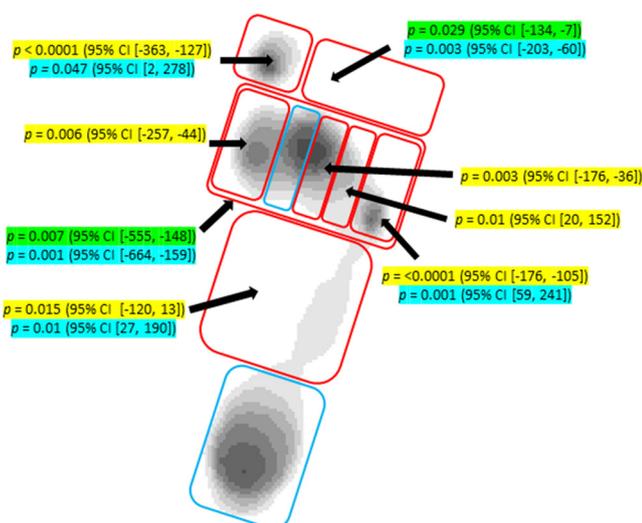
Fig. 2. Results from meta-regression of pressure measurement systems. Regions that were significantly different between systems are outlined in red. Significant differences between emed and MatScan are highlighted in green; differences between emed and footscan are highlighted in yellow; differences between MatScan and footscan are highlighted in light blue (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

effect of neuropathy on peak pressures below forefoot, midfoot, and hindfoot regions. Notably, no significant differences were found between healthy subjects and those with non-neuropathic diabetes, supporting the contention that it is the tissue and gait changes associated with neuropathy that are the primary drivers of increased plantar pressures. These effects were not found to be uniform across the plantar surface of the foot, i.e. they were only significant at certain sites, and indeed were not found to be consistent across the different systems included in this review.

Plantar pressure systems have been used to study foot loading in a number of different health conditions with effects on the musculoskeletal system. In particular, clubfoot [27], rheumatoid arthritis [28], and hallux valgus [29] have all received considerable attention. However, we were not able to identify enough studies meeting our inclusion criteria to include these conditions in this meta-regression analysis.

Changes in the structure of the foot that are associated with increasing BMI have been described in the literature [30], and in the

current analysis we found strong evidence of a positive relationship between peak plantar pressures at forefoot and midfoot regions and BMI. Two of the systems tested showed a significant effect at these regions, although the magnitude of the effect differed, with around 6 kPa increase per unit increase in BMI being estimated from the emed meta-data, and 27 kPa from the footscacn meta-data. As an area that does not have the fat pad structures present at the heel and forefoot, the increase in loading of the midfoot could be related to long term problems of pain and disability at the foot [31].

Individual studies have suggested that the plantar tissues increase in stiffness with age, leading to increased plantar pressures [32], and this was supported by our findings for the forefoot and midfoot regions. Meta-data from one system also suggested that peak pressures below the toes decrease with age. This may result from deformity and/or a redistribution of load to other regions of the foot. Significant differences relating to the percentage of the cohort made up of males and females suggest that, in general, females have lower peak pressures at hindfoot and forefoot regions, but increased peak pressure at the midfoot. These differences may be due to previously described variations in gait and foot structure between males and females [33].

Plantar pressure measurement has several limitations. The loading that is recorded represents only the forces acting perpendicular to the sensing surface, therefore shear forces in the mediolateral and anteroposterior directions are not considered [34]. The use of regional peak pressures makes use of only a small portion of the information collected [35], and alternative methods of processing dynamic pressure data at the pixel level have been proposed [35,36]. There are a number of other discrete variables that can be derived from plantar pressure measurements, such as pressure time integrals, however peak pressures remain the most commonly reported. Additionally, when assessing regional peak plantar pressures, there is a level of subjectivity in defining the regions through the manual or semi-automated methods used by most commercial pressure data analysis systems [37]. Researchers have proposed techniques to improve the anatomical definition of these regions using a combination of externally identified landmarks and motion capture [27], however the majority of measurements are based on plantar pressure data alone. Despite these limitations, peak pressure variables do have the advantage of being easily understandable, and have been demonstrated to be useful in the assessment and treatment of clinical conditions [4,6]. We would also like to draw particular attention to the fact that there is some ambiguity regarding the terms used to describe plantar pressure derived variables. Terms like "peak pressure", "mean peak pressure", and "maximum sensor pressure" were found to be used inconsistently, or without further definition, leading to some

Table 2
Results for mixed effects model of participant characteristics **by system**.

	Moderator Variables					
	Age	BMI	Sex	DIA vs HEA	NEURO vs HEA	NEURO vs DIA
emed						
Midfoot	–	5 (0.0002, [2,8])	–	–	–	–
Medial Midfoot	−1 (0.0057, [-2, -0.3])	6.7 (< 0.0001, [5,9])	0.4 (0.002, [0.2, 0.7])	–	–	–
Lateral Midfoot	–	7.5 (< 0.0001, [5,10])	–	–	–	–
Hindfoot	–	–	−1.5 (0.001, [-2, -0.6])	–	81 (0.02, [13, 149])	–
Lateral Hindfoot	–	–	−1 (0.01, [-2, -0.2])	–	–	–
Met 1	2 (0.0001, [1,3])	–	–	–	92 (0.002, [34, 151])	111 (0.01, [26, 198])
Met 2	–	–	−1.6 (0.01, [-3, -0.4])	–	–	–
Met 3	–	–	–	–	–	–
Met 4	–	3.3 (0.001, [1.3, 5.3])	–	–	34 (0.002, [13,56])	–
footscan						
Midfoot	–	27 (0.004, [9,47])	–	–	249 (0.004, [79, 418])	–
Met 1	–	39.4 (0.01, [8,70])	–	–	–	–
Hallux	−14 (0.007, [-25, -3])	61 (0.01, [12,111])	–	–	–	–
Lesser toes	−5 (0.009, [-8, -1])	26 (0.003, [9,42])	–	–	–	–

Results are presented as: estimated mean effect (p-value, [95% Confidence Interval]). Only regions with statistically significant effects are reported. Met: Metatarsal; HEA: Healthy; DIA: Diabetes; NEURO: Neuropathy. DIA vs HEA presents results for pairwise comparisons between cohort groups.
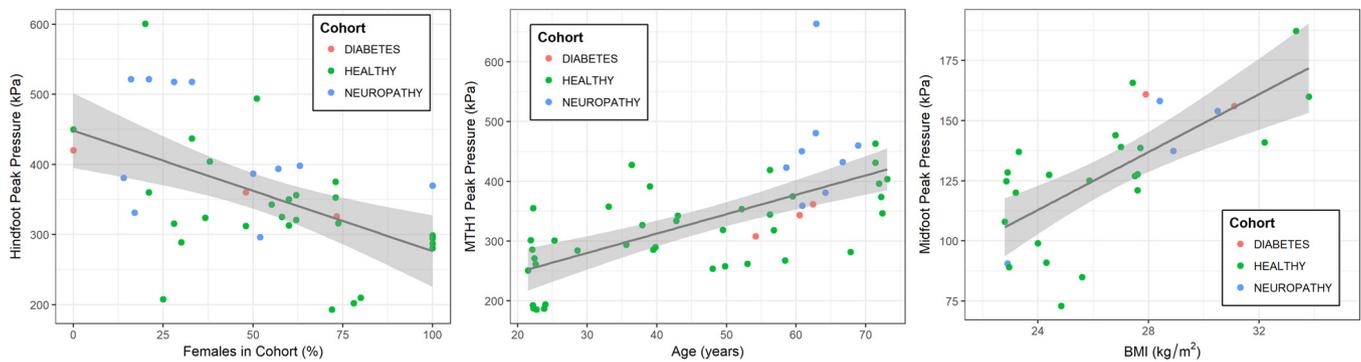
Fig. 3. Scatterplots showing peak pressure results by moderator variables for emed meta-data. Left: Peak pressure under hindfoot vs percentage of females in test cohort. Center: The effect of age on peak pressures under the 1st metatarsal head. Right: the effect of BMI on midfoot pressures. Estimated regression lines with standard error bands are included on all plots. Disease status of participant cohorts are indicated by color.

confusion as to what was actually being reported. It is possible that some of the differences found between systems are as a result of similar terminology being used to describe inherently different variables.

There are several factors that may also influence plantar pressure measurement that we were not able to include in the analysis, mainly due to poor reporting. For example, the number of strides taken before the assessed step can affect the measurement [38], likely due to acceleration effects. The amount of practice the subjects received to allow them to become comfortable with walking naturally over the plate without targeting may also have an effect. In terms of the analysis of the data, the specific version of the hardware and software used was not reported in a significant proportion of studies. This missing information may potentially lead to issues with reproducibility.

Walking speed can have a considerable effect on plantar pressures [24]. However, this was rarely reported in the studies included in this review, and in the majority of cases was described as "self-selected", "comfortable walking speed", or similar. Given the potentially large influence of this variable, we recommend that in future studies, whenever possible information regarding walking speed is included in these types of studies to facilitate comparisons between different datasets. At a minimum, overall contact time has been shown to be moderately correlated with walking speed and can be obtained and reported without requiring any additional equipment.

The limitations of meta-regression approaches have previously been described [39]. To reduce the risk of false positives due to "data dredging", we pre-defined our hypotheses and moderator variables prior to the search, having found evidence in previous studies suggesting that the moderators had a significant effect on plantar loading. In addition, we used separate models for each hypothesis to limit the number of moderator variables included to reduce the risk of overfitting the model to the available data.

Future research may investigate whether there are any systematic effects between measurement systems, and if it is possible to correct for these, thus allowing comparisons to be made between data collected from different sources. Equivalent threshold values, for example, to help define at-risk diabetic feet, may need to be developed for all commonly used measurement systems. Finally, the use of open source software to facilitate reproducible research and avoid issues with variable definitions would provide additional clarity to the literature.

Plantar pressure measurements are increasingly finding clinical applications, particularly in the context of the prescription of therapeutic footwear for diabetic foot disease and those at risk of plantar ulceration. By identifying and analyzing data at the level of the literature, it is possible to draw conclusions with greater confidence than can be provided by one single study. The findings presented in this review confirm the effect of many variables related to plantar pressure measurements, and may help to inform the design of future research in this area and the clinical implementation of the technology.

Conflict of interest

The authors declare that they have no conflict of interest relating to the material presented in this article.

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