Dynamic characteristics of foot development: a narrative synthesis of plantar pressure data during infancy and childhood

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Conflict of Interest statement: The authors declare no conflict of interest.

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Grant support: Eleonora Montagnani is a PhD student funded by The Dr. William M Scholl Unit of Podiatric Development.

Acknowledgement: At the time this article was written, Eleonora Montagnani was a PhD student at the Department of Health Sciences at the University of Brighton, England.

Abstract

Purpose: Quantifying plantar pressure throughout childhood enables clinicians to enhance knowledge of typical changes in foot function. This narrative review aims to describe existing research reporting plantar pressure analysis in typically developing infants and children, to advance understanding of foot development. **Methods:** A narrative approach was adopted; 263 articles were identified and 13 met the inclusion criteria. **Results:** Plantar pressures during walking rapidly change in infancy and childhood. With development, pressures increasingly resemble those in adults; development of initial heel contact, shift in pressure distribution from medial to lateral foot side, decreasing midfoot pressure magnitude. The literature shows varieties of study designs, data collection protocols and analysis. **Conclusion:** This review describes plantar pressure changes occurring as walking develops, emphasizing the typical trajectory of foot function development in infancy and childhood. The present findings will help to elucidate the complex biomechanical development of foot function in typically developing infancy and childhood.

Keywords: foot, gait, pediatric, pressure, development

Introduction

The foot is a complex and unique structure that represents the primary connection between the body and the surrounding environment. [1] Throughout infancy and childhood, foot development reflects complex changes in multiple body systems, such as the neurological, musculoskeletal, and sensory systems, [1,2] underpinning development of both foot structure and function. [2,3] Within this cascade of complex neuro-musculoskeletal events, the foot fulfils specific functions through milestone attainment, including non-weight bearing (grasping and playing with feet, supported and unaided sitting) and weight bearing tasks (pulling to stand, supported and independent walking, running). As walking develops, for example, the foot enhances exploration of the physical and social environment, providing balance and support, and infants perform different walking strategies to progress forward. [4] These strategies likely underpin different foot function characteristics, which can be understood by studying changes in foot biomechanics.

Plantar pressure assessment can be considered an important resource alongside traditional tools of gait analysis (kinematic and kinetic) to understand foot function, also assisting clinicians in their everyday practice. To date, plantar pressure patterns have been investigated during walking in typically developing infants and children via both cross-sectional [7-14] and longitudinal studies. [15-18] Plantar pressure patterns during walking are subject to rapid change in infancy and childhood. [11,15,18] Data has demonstrated significant changes in foot function occurring from the very first months of walking onset. [15-17] These changes occur with increasing strength and postural control [17] and maturation of walking dynamics; development of heel contact pattern, [15] shift in pressure distribution from medial to lateral side of the foot [12,13] and decreasing forces at the midfoot. [16-18] Investigating the typical variations in foot function throughout childhood is important as boundaries of normality are warranted in clinical settings. Accordingly, diagnosis of pathological conditions is often made by comparing data of typically developing reference data. Therefore, understanding the typical profile of foot function throughout periods of development can help inform clinicians when impaired foot development is present. This is essential to enhance diagnosis, intervention decision and to determine pre and post treatment outcomes alongside possible reduction in symptoms. [5,6]

However, plantar pressure patterns were described through a variety of testing protocol, [11,16,18] data collection strategies, [10,11,16] data capture, [9,11,15-17] and analysis. [13,15,16,18]
The diverse nature of the available literature challenges the ability to interpret and make conclusions about the typical foot function development in infants and children. Therefore, the purpose of this review was to appraise the existing literature reporting data on plantar pressure patterns, during walking, in typically developing infants and children. Through undertaking this work, this study aims to enhance understanding of the evolution of foot function from infancy to early and late childhood, contributing to improved knowledge about foot development. This is useful for clinicians to help inform the assessment and (potential) intervention strategies for infants and children. Moreover, this work will help the scientific community recognise the limitations of existing literature, and consider the implications of testing protocols and analysis, to inform future research.

Research purpose

This study aims to describe and summarise existing findings on the typical plantar pressure patterns of infants and children in order to enhance understanding of foot function characteristics and development during typically developing infancy and childhood. The research questions were:

What are the typical plantar pressure characteristics throughout infancy and childhood?

What are the study characteristics of the existing research reporting plantar pressure analysis in infancy and childhood?

Methods

This narrative review has been undertaken to describe, critique and offer interpretation of the existing literature, [19] to help synthesise knowledge to inform clinical practice and research settings. Between August and September 2019, one researcher (EM) undertook searching and screening of literature identified from the search platforms. The three search phases are detailed in Figure 1. In phase 1, search platforms were identified (Science Direct, PubMed, and Google Scholar) as well as keywords and MeSH terms 'pediatric foot' OR 'infant foot' were used and combined using AND/OR with the following keywords and MeSH terms: 'plantar pressure analysis', 'pediatric foot', 'plantar pressure measurements', 'foot pressure', 'loading patterns', 'walking', 'plantar pressure patterns'. A total number of 263 articles were found. In phase 2, inclusion and exclusion criteria were applied to the 263 articles by the same researcher. Article abstracts were screened to ensure they met the inclusion criteria and to identify duplicates. Articles were included if participants in the studies were aged below 13 years, full text was available and plantar pressure data was collected and reported. Exclusion criteria for papers included: not published in a peer reviewed journal, conference papers and written in a language other than English. Articles were excluded if they did not use electronic pressure measurement technologies (e.g., they used foam, ink paper, oils etc.), if they were related to foot orthosis and motor tasks that did not involve loading of the foot. Articles were not explicitly excluded based on the year of publication as the review aimed to capture the breadth of studies reporting typical plantar pressure patterns of the pediatric foot. However, it is recognised that the exclusion criteria relating to measurement technology influenced this. Due to the aim of this work to summarize findings of typically developing infants and children, articles were also excluded if the leading author (EM) found no appreciable criteria within the studies that excluded participants presenting foot pathologies, impaired development, or systemic health problems. Phase 3 involved snowball searching of the reference lists of the identified articles, to ensure that potential studies that were not found within the original search approach were not missed.

Research quality assessment

Synthesis and report of this manuscript was conducted according to standards of the six-item Scale for the Assessment of Narrative Review Articles (SANRA), to ensure the quality of the review as well as to introduce a quality measure for narrative syntheses. [20] Quality of the studies that were included in the review were reviewed according to the Joanna Briggs Institute (JBI) Critical Appraisal Checklist for analytical cross-sectional study. [21] Findings from our quality appraisal are presented in Table 1 *"Quality Assessment of the Studies reviewed with JIB Assessment Tool*".

Results

Thirteen articles matched the inclusion criteria and satisfied the quality appraisal (Table 1) and, thus, were included in the review. The articles are reported in Table 2 *"Summary of typically* *developing plantar pressure studies during infancy, early and late childhood*", and categorized by age of participant(s). According to the literature, we report infancy as up to 2 years of age, as infants learn and master walking abilities. [6, 15-18] Early childhood was defined as the period between 2 and 5 years of age, according to children being in pre-school age, while late childhood as the period between 5 and 13 years of age, acknowledging children in the school-age period. [8-10, 14] In Table 3 *"Maturation of contact area and maximum force during walking in infancy, early and late childhood",* we summarized examples of the pressure data reported in the studies. Data were directly extracted from the studies that reported relative mean changes in the variables selected (in this case, contact area and maximum force). This enabled us to quantify the findings between similar studies and to highlight development of specific foot regions. [10,14,16,18] The data reported (percentages) represent the changes that we can expect to see from 12 to 24 months, from 2 years of age to 5 years of age and from 5 years old to 13 years old.

Infancy: description of the studies and plantar pressure patterns

In infancy, four studies adopted a longitudinal design [15-18] and three adopted cross-sectional design. [7,10,11] The total sample recruited in the studies was 732 and ranged between 7 and 612 in single studies. Studies mainly adopted developmental milestones as their criteria for inclusion, [15-18] as opposed to age. [7,10,11] In all the studies included in this review, speed was self-selected. In four studies infants walked in any direction, [7,16-18] while three studies directed the infants to walk in straight lines over the pressure platform. [10,11,15] Between one to five steps were captured from independent walking trials,[11,16-18] although steps from supported walking trial (where parents held infants' hands) were also captured and combined in some instances.

[18] Novel EMED hardware was most commonly adopted, [7,11,16,18] followed by Footscan RS International [15,17] and Tekscan HR Mat.[11] All the studies adopted regional analysis (dividing the foot in regions of interest), although reported different regions of the feet (Table 1). Common pressure variables reported in the studies included peak pressure (PP), force-time integral (FTI) and contact area (CA), maximum force (MaxF) and contact time (CT). The centre of pressure (CoP) was reported in three studies, [15-17] while pressure time integral (PTI) was not adopted in any studies. Definition of the variables can be found in the Glossary (Table 4). Pressure (PP, CT) and force values (FTI, MaxF), as well as CA values were reported as absolute values. [11,16] CT, FTI, MaxF and CA values however have been mostly normalized to either body weight or expressed as percent (%) of the total value, [7,10,15,17,18] to capture maturation of specific foot regions.

Based upon existing studies, initial foot contact was made mainly with the forefoot, followed by whole-foot contact, and initial heel contact. [15-18] Intra-individual averages of pressure variation were reported once, [16] with findings suggesting that variability in pressure and force values remain consistently high during the first year of independent walking. Pressure was reported to be mainly distributed on the medial side of the foot, [7,10,15] and the hallux was the region with the highest PP during the first eight months of independent walking. [7,15,16,18] PP at the hallux ranged between 120-180 kPa in infants walking independently for the first eight months. [11,15,16] In contrast, PP at the heel ranged between 95.5 kPa and 130 kPa, [7,16,18] while at the forefoot, PP ranged between 78.2 kPa and 110.9 kPa. [16,18] During the first few months of independent walking (12-14 months of age), the CoP was characterised by variable and large oscillations from the medial to lateral aspect of the foot, [15] which became less variable after approximately five months of independent walking experience. [15-17] As walking developed, initial heel contact increased from 5% to 60% of the total footfalls in eight weeks of independent walking and became the typical initial contact pattern after one year of independent walking. [15,17] As presented in Table 3, normalized CA and MaxF at the heel, forefoot and hallux increased during infancy. Normalized CA, MaxF and CT decreased at the midfoot, [10,16,18] even though changes occur more evidently in early childhood (Table 3). Although changes in forces have been observed at the midfoot in infancy, no changes in PP were observed. [11,16-18]

Early and late childhood: description of the studies and plantar pressure patterns

In childhood, we found one longitudinal study [18] and seven cross-sectional studies. [8-14] The total sample assessed was 7,951 and ranged between 14 and 7,176. Samples were commonly defined by age [8-14] and one study defined by developmental milestone. [18] Prescribed walking speed was reported in one study. [8] Children were instructed to walk in straight lines over the pressure platform in all studies but one, [18] where they were free to walk in any direction. One to five steps were captured in all independent walking trials. Again, Novel EMED hardware was the most adopted, [8, 11, 14, 18] followed by Biokinetics, [12,13] Tekscan HR Mat [10] and Musgrave pressure system. [9] All the studies adopted regional analysis and defined different number of foot regions. Neither PTI nor CoP were reported in childhood. PP was reported in all the studies but one,[10] and CA, FTI and MaxF were also reported. Half of the studies normalized the pressure values to body weight or expressed as percent (%) of the total value, [9,11,12,13] while the other half reported absolute values. [8,10,14,18] One study adopted pressure statistical parametric mapping (pSPM) of peak pressure as an analysis technique which was compared to regional analysis. [13]

Based upon the data reported in the studies, there was a shift in pressure distribution from medial to lateral side in early childhood, [9,18] and this pattern was consistently present in late childhood. [6,9,10] The heel was the most loaded region in early and late childhood. [12,18] In early childhood, PP at heel ranged between 169 kPa and 212.5 kPa, [9,18] with the lateral heel being subject to higher PP (119 kPa) than the medial (99 kPa). [8,9] In late childhood, PP at the heel increased (280 kPa). [12] CA and MaxF continued increasing at the heel, forefoot, and hallux in early and late childhood, [10,18] although changes were less evident than in infancy (Table 3). Forces decreased at the medial midfoot and increased at the lateral forefoot (Table 3). Pressure was reported to increase on the central metatarsals in late childhood, which was also confirmed by SPM analysis. [13] There were no changes in PP at the midfoot from early to late childhood. [11,18]

Discussion

This narrative review has summarized existing literature on typical plantar pressure patterns of infants and children, to enhance knowledge of the complex development of foot function in typically developing infancy and childhood. Moreover, we highlighted some key characteristics to consider within the current literature, to improve future work in the field.

Typical plantar pressure characteristics and development from infancy to childhood

Pressure data in infancy has been reported from the onset of walking, which defines the period when infants start to take their first independent steps (12-14 months). [7,16,18,22]

From the onset of walking, infants showed poor balance and postural control, and this was supported by the observation of irregular medio-lateral and anterior-posterior oscillations of the CoP. [15-17] Whilst walking experience augment, infants gradually develop stability and motor control and walking dynamics improve as the CoP oscillations become more regular, the stance phase becomes shorter, and there is a change in initial contact pattern from forefoot to heel. [15,16]

Moreover, changes with decreased MaxF, CT, and CA in the midfoot have been also demonstrated (Table 3). [10,15,17] In typically-developed feet, the arched midfoot serves as lever to transmit pressure and force stored at heel contact to the forefoot, [23] thereby preventing the midfoot to be subject to high pressures. In infancy, the decreasing pressure and forces in the midfoot demonstrates that this typical midfoot function is present from the first year of independent walking, suggesting rapid changes towards a typical plantar pressure distribution throughout the foot. Improvement in walking dynamics is possible also because bones ossify and soft tissue increase in strength, [2,24] providing a more stable and solid structure. Therefore, as neuro-musculoskeletal system matures, [1,2,15,24] foot function changes take place. This means during infancy, there is an increasing shift of pressure towards the heel at initial contact, which passes to the forefoot and the hallux through the midfoot, resembling the typical adult walking pattern. Nevertheless, intra-individual variation of pressure and force variable was reported being consistently high during the first year of independent walking. [16] Therefore, high variability of pressure and force patterns can be expected in infancy due to the ongoing development of motor control.

In early childhood, we see continuous changes towards development of the typical roll over pattern. Pressure is initially distributed from the medial to the lateral side of the foot during walking, [9] with findings confirming a continuous shift towards lateral foot pressure distribution in late childhood. [10,11] However, during early childhood, the medial side of the foot is still subject to higher pressure and forces in comparison with the lateral. [8] These findings lead us to assume that the higher-pressure on the medial aspect of the foot during walking may be accentuated by the ongoing foot structural development occurring between early and late childhood. Therefore, the foot continues its structural and functional development in the transition to late childhood, suggesting also that the efficient transfer of force from medial to lateral side does not occur as we typically appreciate in healthy adults' feet.

In late childhood, studies reported the heel to be subject to greater pressure than in infancy and early childhood. [11,14,18] This can be explained as increasing body weight in comparison with younger children and infants. Moreover, improved walking skills, balance, and postural control lead to increasing walking speed during walking, which was showed to affect pressure patterns during infancy and childhood. [25] Therefore, during late childhood, the midfoot transfers the forces experienced at heel contact to forefoot and hallux, which is also subject higher pressure and forces as body is propelled forward to push off. Thus, the typical characteristics of an adult-like foot-ground interaction start to be increasingly evident from late childhood.

Characteristics of the existing literature

Describing the characteristics of foot function development from infancy to childhood has been a non-trivial task. Based upon existing evidence, comparing, and combining the results among the studies was challenging due to the heterogeneous choices of sample definition, study design and testing protocol. For example, we found that data has been collected in a wide combination of cross-sectional and longitudinal designs, on participants recruited by either age or developmental milestone, who were either led to walk in straight lines independently or supported by parents or both. This means we must draw considerations about foot function characteristics and development with care due to these inconsistencies among experimental designs, and thus among their findings. Moreover, studies demonstrated different approaches to data capture and analysis. For example, in Table 2, we reported that different technologies have been used to capture pressure data. This is an important factor to consider within the pediatric field as these systems have different resolution, the steps captured in infants and young children are smaller in comparison with adults, as well as more variable in pressure distribution, shape and dimensions. Therefore, a low-resolution system is likely to influence the quality of pressure information, hence interpretation of the data. The resolution of the resulting data is also influenced by the number of steps analyzed in the studies (often $n \leq 5$) and the masks applied. Simplifying small numbers of data to five regions, for example, excludes a large proportion of the information collected, [26] with pSPM reducing this limitation. [13] Studies also used a wide variety of pressure variables to describe plantar pressure patterns in infancy and childhood. Among them, the CoP was barely used, [15-17] and thus our understanding of balance and postural control development is scarce and warrants further investigations. The most common variables used were PP and force metrics (e.g., MaxF and FTI). When considering pressure variables, it is important to highlight that changes in PP in the midfoot have not been demonstrated, [11,14,16-18,20] although other pressure and force values considerably changed. This can be attributed to either or both: (i) the use of insufficient number of regions of interest that limit the pressure information occurring within and between foot regions (ii) the use of PP as a metric to describe foot function characteristics, which by definition only reflects the higher pressure occurring in a specific region of the foot over the stance phase. Based on these findings, further work is warranted to establish whether other metrics could be used to represent the overall plantar pressure characteristics (e.g., CoP, PTI, FTI). Future works should also seek to determine the optimal approach to analyze pressure data in infancy and childhood, which yield data that advance an improved understanding of the inter-segmental coordination of the developing foot joints.

Conclusions

In typically developing infants and children, plantar pressure studies examined how foot function changes from the onset of walking, underpinning initial foot function and gait development. The review of the literature highlighted that there are considerable changes in force and pressure values at foot during walking in infancy. Furthermore, changes in contact patterns, force and pressure values are evident within the first year of independent walking and continue through early and late childhood. With this review however, we emphasize that creating a standardised protocol to analyze infants and children pressure data is difficult, as it presents challenges in terms of study design, testing protocol, sample definition as well as approaches to data capture and analysis. These aspects likely limit the extent to which findings can be compared among studies regarding the characteristics of foot function and its development. Therefore, additional work in the field of plantar pressure is needed to develop an optimal methodological framework that will provide a more insightful understanding of foot function characteristics and development in infancy and childhood.

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Figure Legend

FIGURE 1. Flow Chart of the Approach to the Literature Search.

FIGURE 1.

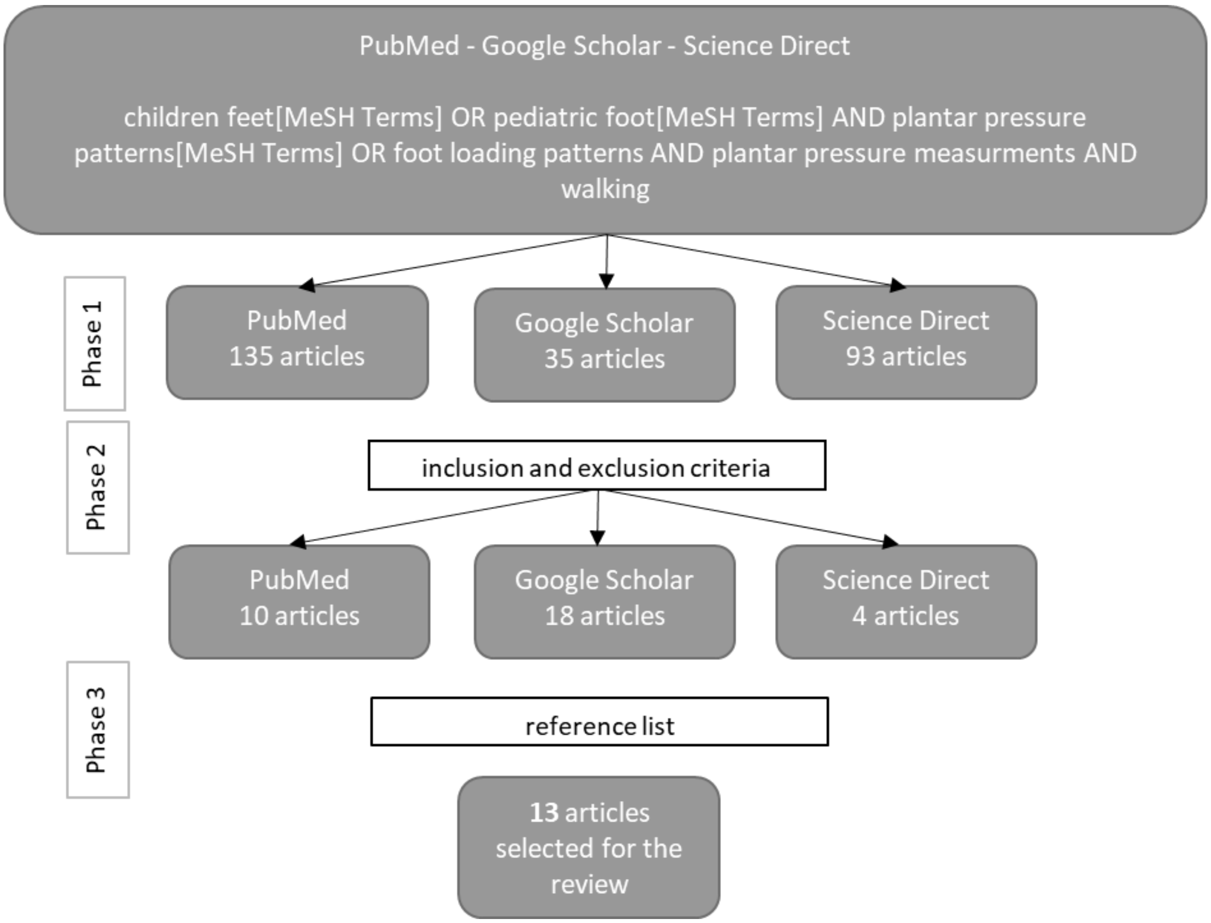
PubMed - Google Scholar - Science Direct
children feet[MeSH Terms] OR pediatric foot[MeSH Terms] AND plantar pressure patterns[MeSH Terms] OR foot loading patterns AND plantar pressure measurments AND walking
Phase 1
PubMed 135 articles
Google Scholar 35 articles
Science Direct 93 articles
Phase 2
inclusion and exclusion criteria
PubMed 10 articles
Google Scholar 18 articles
Science Direct 4 articles
Phase 3
reference list
13 articles selected for the review

TABLE 1. Quality Assessment of the Studies reviewed with the Joanna Briggs Institute (JIB) Assessment Tool [19]

Studies	Were the criteria for inclusion in the sample clearly defined?	Were the study subjects and the setting described in detail?	Was the exposure measured in a valid and reliable way?	Were objective, standard criteria used for measurement of the condition?	Were confounding factors identified?	Were strategies to deal with confounding factors stated?	7. Were the outcomes measured in a valid and reliable way?	8. Was appropriate statistical analysis used?	Overall appraisal
Alvarez et al. 2008	Yes	Yes	Yes	Yes	Not applicable	Not applicable	Yes	Yes	Include
Bertsch et al. 2004	Yes	Yes	Yes	Yes	Not applicable	Not applicable	Yes	Yes	Include
Bosch et al. 2010	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Include
Bosch et al. 2007	Yes	Yes	Yes	Yes	Not applicable	Not applicable	Yes	Yes	Include
Hallemans et al. 2003	Yes	Yes	Yes	Yes	Not applicable	Not applicable	Yes	Yes	Include
Hallemans et al. 2006	Yes	Yes	Yes	Yes	Not applicable	Not applicable	Yes	Yes	Include
Henning et al. 1991	Yes	Unclear	Yes	Yes	Not applicable	Not applicable	Yes	Yes	Include

Henning et al. 1993	Yes	Unclear	Yes	Yes	Not applicable	Not applicable	Yes	Yes	Include
Kellis, 2003	Yes	Yes	Yes	Yes	Not applicable	Not applicable	Yes	Yes	Include
Mesquita et al. 2019	Yes	Yes	Yes	Yes	Not applicable	Not applicable	Yes	Yes	Include
Muller et al. 2012	Yes	Yes	Yes	Yes	Not applicable	Not applicable	Yes	Yes	Include
Phethean & Nester, 2012	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Include
Phethean et al. 2014	Yes	Yes	Yes	Yes	Not applicable	Not applicable	Yes	Yes	Include

TABLE 2. Summary of Typically Developing Plantar Pressure Studies during Infancy, Early and Late Childhood

				Plantar pressure studies during infancy			
Authors (year of publication)	**Study design**	**Age group and sampling**	**Plantar pressure technology**	**Testing protocol**	**Nature of trials**	**N of trials and/or steps tested**	**Da ap**
[18] Bosch et al., (2010)	Longitudinal	14 – 18 months of age and recruited by developmental milestones	Emed ST, Emed X (Novel, GmbH, Munich)	Self-selected speed, free walking. Each participant analyzed over 9 years	Supported and independent walking trials	5 steps for both left and right foot per participant	Re (he for an
[16] Bertsch et al., (2004)	Longitudinal	14 – 16 months of age and recruited by developmental milestones	EMED ST4 (Novel, GmbH, Munich)	Self-selected speed, free walking. Each participant analyzed 4 times over one year	Supported and independent walking trials	5 steps for both left and right foot per participant	Re (he for an
[15] Hallemans et al., (2003)	Longitudinal	Age not specified. Independent walking 0-2 months	Footscan platform (RS scan International) + AMTI force plate	Self-selected speed, directed walking. Each participant analyzed 2 times in 6 weeks	Not reported	Not reported	Re (H lat an me he
[17] Hallemans et al., (2006)	Longitudinal	Age not specified, recruited within a week of 2/3 independent steps	Footscan platform (RS scan International) + AMTI force plate	Self-selected speed, free walking. Each participant analyzed 10 times in 20 weeks	Independent	1 step per participant	No
[11] Muller et al., (2012)	Cross-sectional	12-24 months of age and recruited by age	EMED X (Novel, GmbH, Munich)	Self-selected speed, directed walking. Each participant analyzed once at each age	Independent	3 to 5 steps per participant	Re (he for usi 55 tot he

[10] Alvarez et al., (2008)	Cross-sectional	Infants aged less than 24 months of age (mean age 1.56 years) and recruited by age	Tekscan HR Mat (South Boston, MA)	Self-selected speed, directed walking. Each participant analyzed once	Not reported	3 steps per participant	Re (he me lat me
[7] Henning & Rosenbaum (1991)	Cross-sectional	14 – 32 months of age and recruited by age	EMED F01 (Novel, GmbH, Munich)	Self-selected speed, free walking. Each participant analyzed once	Not reported	3 steps per participant	Re (m lat mi me an

Plantar pressure studies during early and late childhood								
Authors (year of publication)	**Study design**	**Age group and sampling**	**Plantar pressure technology**	**Testing protocol**	**Nature of trials**	**N of trials and/or steps tested**	**Data analysis approach**	**Pressure variables (and units)**
[18] Bosch et al., (2010)	Longitudinal	2 – 10 years of age and recruited by developmental milestone	Emed ST, Emed X (Novel, GmbH, Munich)	Self-selected speed, free walking. Each participant analyzed 17 times over 9 years	Supported and independent walking trials	5 steps for both left and right foot per participant	Regional analysis (heel, midfoot, forefoot, hallux and toes)	PP (kPa), MaxF (% BW), CA (%Total foot CA), AI
[9] Kellis (2001)	Cross-sectional	3 years of age and recruited by age	Musgrave pressure platform system	Self-selected speed, directed walking. Each participant analyzed once	Independent	1 steps per participant	Regional analysis (heel, lateral and medial midfoot, medial central and lateral metatarsal heads,	PP (kPa) and mean PP

							hallux, second to fifth toes)	
[12] Phethean & Nester (2012)	Cross-sectional	4 to 7 years of age and recruited by age	Biokinetics dynamic optical pedobarograph (Biokinetics Inc., Bethesda, USA),	Self-selected speed, directed walking. Each participant analyzed once	Independent	5 steps for both left and right foot per participant	Regional analysis (heel, lateral and medial midfoot, hallux, metatarsal heads 1-5)	PP (kPa), FTI (Ns),
[13] Phethean & Nester (2014)	Cross-sectional	4 to 7 years of age and recruited by age	Biokinetics dynamic optical pedobarograph (Biokinetics Inc., Bethesda, USA),	Self-selected speed, directed walking. Each participant analyzed once	Independent	1 steps per participant	Two regional analysis approaches (1. heel, midfoot, forefoot, hallux and toes; 2. medial and lateral heel, medial and lateral midfoot, first to fifth metatarsal heads, hallux and toes)	PP (kPa)
[11] Muller et al., (2012)	Cross-sectional	2 to 13 years of age. Each age corresponding to an age group and	EMED X (Novel, GmbH, Munich)	Self-selected speed, directed walking. Each participant analyzed	Independent	3 to 5 steps per participant	Regional analysis (heel, lateral midfoot, medial midfoot, hallux, and first,	PP (N/cm2), FTI (Ns), total foot CA (cm2) only, AI

		recruited by age		once at each age			second, third, fourth and fifth metatarsal heads)	
[10] Alvarez et al., (2008)	Cross-sectional	3 to 7 years of age divided in 2 groups (2-5; older than 5) and recruited by age	Tekscan HR Mat + Research Foot Module (South Boston, MA)	Self-selected speed, directed walking Each participant analyzed once	Not reported	3 steps per participant	Regional analysis (total foot, heel, midfoot, forefoot)	MaxF (%BW) % of stance spent across the regions
[8] Henning & Rosenbaum (1994)	Cross-sectional	6 to 10 years of age and recruited by age	EMED F01 (Novel, GmbH, Munich)	Instructed walking, speed (1.0 meters/sec). Each participant analyzed once	Independent	5 steps per participant	Regional analysis (medial and lateral heel, midfoot, first, third and fifth metatarsal heads, hallux)	PP (kPa), FTI (%Total foot)
[14] Mesquita et a., (2018)	Cross-sectional	4 to 10 years of age and recruited by age	Emed AT-4 (Novel GmbH, Munich, Germany)	Self-selected speed, directed walking. Each participant analyzed once	Independent	5 steps for both left and right foot per participant	Regional analysis (heel, midfoot, forefoot, hallux and toes)	PP (kPa), MaxF (% BW), CA (cm2)

Abbreviations: PP, peak pressure; CA, contact area; CT, contact time; FTI, force-time integral; CoP, center of pressure; MaxF, maximum force; % total, relative to the total variable selected; % BW, relative to the subjects' body weight; % stance, relative to the full stance phase; AI, arch index

TABLE 3. Maturation of Contact Area and Maximum Force during Walking in Infancy, Early and Late Childhood.

	Contact area (% of total foot area)			Maximum force (% of body weight)		
Regions of interest	**Infancy (12-24 months)**	**Early childhood (2-5 years)**	**Late childhood (5-13 years)**	**Infancy (12-24 months)**	**Early childhood (2-5 years)**	**Late childhood (5-13 years)**
Heel	↑ 3.3%	↑2.1%	↑2.6%	↑13.3 – 17%	↑13.5	↓0.4% – 4.1%
Midfoot	↓2.7% - 3.6%	↓ 6.4%	↓ 0.4% - 0.6%	↓ 4.1 – 5.5%	↓15.9%	↓2.9%
Medial midfoot	N/R	N/R	N/R	N/R	↓8.9%	↓4.1
Lateral midfoot	N/R	N/R	N/R	N/R	↓1.1%	↓2.9%
Forefoot	↑5.2%	↑2.3%	↑0.7%	↑15.3 – 22.7%	↑8.1	↑10%
Medial forefoot	N/R	N/R	N/R	N/R	↓0.3%	N/R
Lateral forefoot	N/R	N/R	N/R	N/R	↑9%	↑4.9%
Hallux	↑0.5%	↑0.8%	↑0.2% - 0.4%	↑0.5 – 2.2%	↑4.7%	↓1 – 2.5%
References	16, 18	18	14, 18	16, 18	10, 18	14, 18

Abbreviations: ↑, value increasing; ↓, value decreasing; N/R, regional data not reported

TABLE 4. Glossary

Variable	Measurement unit	Description
Peak pressure (PP)	kPa	The singular peak pressure for a single sensor at a single point in time across the foot and/or foot region detected during a step cycle
Contact area (CA)	cm^2	The total area of the foot and/or its regions in contact with the ground during a step cycle
Contact time (CT)	ms	The total time the foot and/or its regions spend in contact with the ground during a step cycle
Maximum Force (MaxF)	N	The highest force in the foot and/or its regions during a step cycle
Force-time integral (FTI)	$N.s^{-1}$	The area under the force-time curve of the foot and/or its regions during a step cycle
Centre of pressure (CoP)		The point application of the force vector during a step cycle
Pressure-time integral (PTI)	$kPa.s^{-1}$	The area under the pressure time curve of the foot and/or its regions during a step cycle