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Review

Pedobarography and foot homeostasis in the pediatric population: A narrative review

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Abstract: Foot homeostasis refers to a delicate and intertwined equilibrium of various body structures, including the neural and musculoskeletal elements. It reflects the ability to coordinate body movements, balance, and gait, using the functional feedback-operative foot-brain axis. Disturbances of this system cannot be underestimated in the childhood developmental phase, for they contribute to the child's health status and health complications in adulthood. The foot dysfunction in children is an underrecognized area of homeostatic well-being. This article summarizes recent updates on foot homeostatic complications evolving from children's metabolic disorders, exemplified by diabetes, lipid dysfunction, and obesity, all strongly on the rise in the contemporary world. The review advocates the broader use of pedobarography, a safe, noninvasive, and effective method of foot examination. Pedobarography, developed for adult use, is suitable for the pediatric population, offering a unique assessment of the musculoskeletal system based on plantar pressure distribution while standing or walking. It is poised to play a significant role in clinical practice. The foot-brain axis structural distortion may be an early sign of neuromuscular or neuropathic metabolic disorders, exemplified by diabetes or obesity, ailments on the rise in childhood. Thus, foot examination helps diagnose and manage children's disorders, including treatment and rehabilitation follow-ups.

Keywords: foot homeostasis; metabolic disorders; pediatric population; rehabilitation

1. Introduction

Foot homeostasis is the ability to maintain internal stability while adapting to external environmental changes. This is one of the oldest phylogenetic traits, dating back to the dawn of humanity. In olden times, evolutionary homeostasis was associated with the biomechanical needs of gradual lifestyle changes moving away from endurance-suited running and walking for hunting to more sedentary behaviors and modern locomotion [1]. In recent decades, predictive foot homeostasis has developed, which is strongly sensitive to pathophysiological consequences of metabolic disorders, such as diabetes, obesity, and dyslipidemias, all increasingly frequent childhood disorders [2–4]. Homeostasis entails forecasting systems for detecting pathological processes. Thus, it also has a preventive role, which cannot be underestimated, particularly in the pediatric population.

Foot homeostasis refers to a complex equilibrium of various body structures, including neuromuscular and skeletal elements. It coordinates body movements, body balance, and gait using the functional feedback-operative foot-brain axis. Foot deformities are common and challenging health issues for pediatric orthopedists and physiotherapists. During early childhood, the foot structure develops during the transition time from standing to walking. The development of walking ability raises the potential for foot and neuromuscular disorders [5].

A prompt diagnosis of foot disorders is essential for treatment and health damage control. Assessing congenital or acquired foot disorders, it should not be overlooked that the issue is not a focal pathology but potentially affects the entire child's musculoskeletal axis. Despite knowledge about the general influence of foot disorders on body posture and motion, the treatment far too often concentrates on local correction. In younger children, a correlation exists between the spatial foot shape and the development of hip and knee joints. Foot growth occurs with the whole body's motor development, so foot defects may reflect compensatory consequences of body distortions [6]. Therapy ought to be based on two principles—adequate early intervention and regularity. These principles are also paramount for effective rehabilitation [7].

Foot diagnostics should be based on reliable methods with strictly defined classifications. Among several available methods, pedobarography becomes prominent [8]. It is a non-invasive examination assessing the plantar pressure distribution during standing or walking, which translates into the biomechanics of the musculoskeletal system. The method of pedobarography was created for adults but is also suitable for kids. It diagnoses foot disorders but also tracks the course and effectiveness of their management [9]. The examination may be performed during routine medical examinations or as part of physiotherapeutic treatment [10]. It takes place on a platform supplied with insulated pressure sensors or inserts in the following conditions:

- Dynamic mapping of plantar pressure distribution changes while walking, including postural leg-dependent stability.
- Static, showing the pressure distribution while standing.

The diagnostic tools for the foot shape assessment are currently insufficient. The available posture defect schemes refer to the foot arch and its subjective evaluation. They do not inform about which foot area is defective. The primary aim of this review was to get insights into the potential of pedobarographic examination for the diagnosis and rehabilitation of foot disorders in childhood. The secondary aims were to provide explanatory clinical perspectives on the connections between pediatric foot deformities and metabolic disorders, exemplified by diabetes and obesity, and genetic or otherwise rare neuromuscular disorders that involve plantar pressure changes.

2. Methods

We searched the English-language medical literature concerning pedobarography in children published between March 2013 and March 2024 in the PubMed and Google Scholar databases. The standard string of terms code adopted was (("children") AND ("pedobarography" OR "underfoot pressure distribution" OR "plantar pressure distribution")). It was followed by a complex code of (("child" OR "pediatric") AND ("pedobarography" OR "plantar pressure" OR "foot pressure")).

The latter search string was used to minimize the possibility of non-exhaustive coverage of the literature.

Inclusion criteria included:

- Original reports of controlled clinical trials, meta-analyses, systematic reviews, and published conference proceedings.
- Research and methodological reports concerning foot disorder diagnosis in children.
- Reports on physiotherapeutic rehabilitation.
- Reports on therapy plans and the illustration of pedobarography functionality.
- Redundant articles, observational reports, commentaries, short communications, and publications otherwise deficient in providing evidence-based results were excluded.

3. Results

We found 53 papers in PubMed and 719 in Google Scholar referring to "children AND pedobarography", 27 and 8,660 papers, respectively, referring to "children AND underfoot pressure distribution", and 90 and 16,700 papers, respectively, referring to "children AND plantar pressure distribution," which makes a total of 170 papers in PubMed and 26,079 in Google Scholar. The complex code search returned 167 and 8,310 papers in PubMed and Google Scholar, respectively. After the abstract screening, we considered the most relevant publications for discussion in this review. The total set of these publications encompassed 80 from PubMed and another 80 from Google Scholar. The assessment of relevance has an inherent subjectivity linked to the assessor's perceptual interpretation of importance. To mitigate this biasing aspect, the choice was based on criteria set up for the Scale for the Assessment of Narrative Review Articles (SANRA). SANRA encompasses study originality, proper formulation of aims and outcomes, evidence-based findings, adequately presented data, and support of arguments by references [11]. We used SANRA for the self-check assessment of the present review's quality, which yielded 10 points out of the 12 possible. The completed SANRA form is presented in the supplementary material to this paper. The selected publications address functional characterization of plantar pressure patterns during children's gait development, healthy foot profiles from the ages of 1.5 to 15 years, flatfoot, clubfoot, and foot changes in the metabolic derangements of diabetes and obesity. The others pertained to neuromuscular and skeletal disorders, mostly scoliosis, and children's rehabilitation. Single items were concerned with the foot in rare genetic diseases, such as Sèvres' disease, Charcot-Marie-Tooth's disease, Dravet syndrome, polydactyly, rheumatoid arthritis, and cerebral palsy.

4. Discussion

4.1. Foot developmental disorders

Dynamic pedobarography has been useful for the functional characterization of plantar pressure patterns during the development of children's gait. In a study by Dulai et al. [6], the group consisted of 102 children aged 2–17, including 52 girls.

Each participant had the dynamic gait-related plantar pressure distribution mapped three times on each foot. The maximum pressures in individual foot zones, including the big toe, heel, middle forefoot, lateral forefoot, second-to-fifth little toes, and metatarsals, were assessed. The main findings were that, compared to other plantar zones, forefoot pressure was lower in younger children, while it was lower in the forefoot but higher in the midfoot area in the older ones. Moreover, the foot zone pressure distribution in the oldest children, aged 15–17, was like that in adults. Thus, the skeletal foot components mature in adolescence, resulting in the functional features seen in adults. The authors state that dynamic pedobarography measurements can be considered a reference point in the clinical evaluation of children with foot deformities affecting gait.

Pedobarographic measurements were valuable in following the development of a healthy foot profile in children aged 1.5–15 years. A study by Demirbüken et al. [12] analyzed foot images of 146 patients with unnoticeable abnormalities in three age groups: below 2, 2–5, and over 5 years. The plantar pressure distribution was a limiting factor in setting the group age. The percentage distribution of pressure forces varied with age in every foot zone. Measurements enabled the creation of foot profiles for specific ages, a practical tool for assessing children's foot disorders.

The pedobarographic image shows irregularities related to external non-diseased clues. This is exemplified in studies investigating the impact on foot loading of wearing heavy school backpacks in children aged 6–13 years [5, 6]. The results show that spine overloading puts excessive stress on the forefoot, contributing to biomechanical disturbances of the locomotor system. This practical topic has not yet been sufficiently explored in the context of load standardization and proper prophylactic countermeasures.

A flatfoot, or pes planus, is a common defect that affects 30% of children. This defect lowers the foot's longitudinal arch. The treatment is conservative, requiring a prompt diagnosis, which is hardly achievable using an old planto-conturographic method, particularly in conditions like obesity when the actual foot contour is blurred, leading to false-positive results [13, 14]. A pedobarography examination successfully aids in overcoming such impediments. It diagnoses the condition and helps choose the most effective rehabilitation. That has been confirmed in a study conducted on 60 children with this deformation in whom the disorder improved with corrective shoes and rehabilitation exercises [12]. In a group of patients, footwear with an inner insole was used to raise the longitudinal arch. In another study, shoes equipped with the Thomas heel were used, while yet another group was subjected to a corrective exercise program alone. Each group consisted of 20 children. Pedobarographic examinations were conducted in static and dynamic routines before and after protocol completion. All the groups showed improvements, but the best result was obtained using the shoes with an inner insole lifting the longitudinal foot arch. In children with pes planus, lower peak pressures in the rear and middle foot zones are emphasized as a sign of improvement, the essential markers recorded in pedobarographic examinations [15].

The treatment and rehabilitation of clubfoot is another challenge. It is the second most common birth defect, after hip dislocation [14, 16]. However, it may also be secondary to neuromuscular sequelae of meningeal hernia or polio inflammation. The worldwide annual incidence of congenital clubfoot is 1 per 100,000 newborns, occurring twice as often in boys as in girls [17]. The Ponseti method, which involves casting and percutaneous tenotomy of the Achilles tendon, followed by the use of a foot abduction brace to counter relapses, is an effective treatment. The effects are markedly enhanced by repeat pedobarographic examinations, which better illustrate pressure differences during walking and provide more details of dynamic foot load and residual deformations than the kinematics of the sagittal plane alone [18–20]. The Ponseti pedobarography-enhanced technique appears superior to surgical interventions, particularly in children about the age of 5 years [21].

A common pathology is sterile bone necrosis, which occurs in 2–10 children per 10,000. It is characterized by non-pathogenic bone and cartilage degradation secondary to the discordant connection between the epiphyseal vessel supply and epiphyseal closure during the growth period. The disease involves a palette of about 40 pathological conditions sharing a similar clinical course and picture. One of them is Sever's disease, avascular calcaneus necrosis, which mostly develops at puberty age, is three times more common in boys than girls, and affects both heels in over 60% of cases. Pedobarographic examinations play a key role in the management of Sever's disease and the assessment of risk factors for its occurrence [22].

Pedobarography is also of use in children with Charcot-Marie-Tooth disease, a hereditary neuropathy leading to muscle weakness and sensory loss. It affects 1 in 2,500 children. They have characteristic foot deformities such as pes cavus (a high-arched foot), peroneal muscle atrophy, foot drooping while walking, called steppage gait, and weak ankle reflexes. Dynamic pedobarography is used in preparation for surgical corrections and post-surgery to check the corrective effects on the plantar pressure distribution pattern and to rehabilitate the foot loading. No other past radiological examinations would have been able to fulfill the check role [23].

Another example of using pedobarography is to check the effectiveness of surgery in children suffering from polydactyly. Polydactyly is a birth defect in which extra toes are present. The polydactyly type depends on the location of extra toes, such as preaxial toes on the tibial side of a big toe or postaxial toes on the peroneal side of a small toe. Surgical resection is necessary to uphold foot biomechanics and gait quality. A study by Farr et al. [24] investigated 39 children aged 3 to 13 years. Resection was performed in different foot areas in both preaxial and postaxial polydactyly. Pedobarography allowed for the observation of post-surgery changes in the plantar pressure distribution pattern. This foot examination technique has also been successfully used in children treated and rehabilitated for rheumatoid diseases. The most common rheumatoid disorder is juvenile idiopathic arthritis, an autoimmune illness of unknown etiology. It occurs in 80–100 children per 10,000 in Poland. It can be either sparse or polyarticular. The disease requires early treatment and rehabilitation to prevent disability. Pedobarography offers invaluable insights into the management of lower limb arthritis [25].

Pedobarography enables the detection of foot deformities in children with thoracic scoliosis, which induces a three-dimensional spine defect. The prevalence of idiopathic scoliosis in children and adolescents ranges between 0.5% and 5%, with 3M new cases yearly in the US. Pedobarography is indispensable for executing the effective physiotherapeutic paradigm in scoliosis. Aside from scoliosis detection, pedobarography shows asymmetry in limb loading, which may be detrimental for gait in later years of life [6, 26].

The importance of pedobarography reaches beyond the diagnosis and rehabilitation of foot deformities. The technique is a valuable tool in plantar fasciitis, particularly in the case of unsuccessful conservative treatment and persisting pain requiring surgical interventions. Pedobarography helps diagnose the underlying pathogenetic causes, including insights into the excessive mechanical stress caused by abnormal foot posture, neuropathic pain, aseptic osteonecrosis, or cancer [27]. This technique also helps detect the frequency and pattern of foot abnormalities in cerebral palsy and paralytic foot in children with spastic hemiplegia [28]. The talipes valgus deformity is common in children with hemiparesis. It is associated with increased foot dorsiflexion and the ankle and knee extension moments on the affected side [8]. Combining a system of sensors recording pressures on the plantar surface with advanced computerized video recordings enables the visualization of the effect of therapy [29].

Finally, pedobarography has characterized the foot-ground contact pattern in children with Dravet syndrome. This is a rare genetic drug-resistant myoclonic epilepsy, with the incidence rate of 1 to 20,000–40,000 live births. A paper by Wyers et al. [30] investigated a group of 31 sufferers from this syndrome, aged 5 to 32 years. The foot-ground contact showed time-related abnormalities, with a shortened heel contact time and elongated metatarsal contact time, compared with healthy individuals. Additionally, gait immaturity and instability were detected; the findings strongly suggested the implementation of pedobarographic examinations at the onset of medical procedures.

4.2. Foot metabolic disorders

4.2.1. Obesity and diabetes

Obesity and diabetes, often going in tandem in children, form a global health crisis, driven by socioeconomic and lifestyle factors. Currently, 8.5% of children and adolescents worldwide are obese, with a body mass index (BMI) > 95th percentile. In highly developed countries, the obesity rate approaches 50% (e.g., USA 19.3%, Puerto Rico 28.4%, and Saudi Arabia 49.7%), while the lowest rates are in Central Africa (2.4%) and Vanuatu (0.4%) [2]. Diabetes, a frequent accompaniment of obesity, also takes its toll. In Europe, the incidence of type 1 diabetes (T1D) in children amounts to 295,000 cases, which is the highest rate in the world [3]. Type 2 diabetes (T2D) showed a 1.5-fold increase between 2012–2023 vs. 2000–2011. In countries with a high socio-demographic index (SDI), a composite indicator of development status, the incidence of T2D is 9.3/100,000, which contrasts with 3.6/100,000 in those with a low SDI. Obesity increases the risk of T2D in children 4-fold, which is further enhanced by genetics, lack of physical activity, a highly processed diet, and other factors [4, 31]. Early interventions, such as weight management and behavioral therapy, are essential for preventing complications.

T1D and T2D carry a risk of serious foot complications, known as diabetic foot syndrome, although the full-blown syndrome is less common in children than in adults. A key problem is homeostatic disruption of peripheral nerve function, caused by destabilization of their internal environment, known as diabetic neuropathy. The sensory disturbances in foot touch, pain, or temperature follow. Chrzanowska et al. [3] have reported cases of foot drop in children with newly diagnosed T1D, emphasizing that although severe neuropathies (e.g., peroneal nerve damage) are rare, they can herald the disease. Subclinical neuropathy is more frequent. Wysocka-Mincewicz et al. 2023 [32] have shown that 64% of T1D adolescents present with abnormalities in nerve conduction, despite the absence of clinical symptoms. In the 2017 Search for Diabetes in Youth Study, Dabelea et al. [33] reported that peripheral neuropathy in adolescents occurs in 22% of T2D vs. 7% of T1D, highlighting the greater risk of complications in the former. Still, hyperglycemia and obesity are the key factors preceding structural neuropathic foot changes in T1D [2]. These factors lead to misalignments in foot biomechanics. Thus, annual foot examinations in children and adolescents with diabetes are advised from the age of five years as preventive or progress monitoring measures in diabetic foot syndrome [34]. About 58% of children with T1D reveal abnormalities in nerve conduction, despite unremarkable changes in the musculoskeletal domain [35]. Nonetheless, the neural and vascular damage underlying the diabetic foot peripheral sensory neuropathy is the main risk factor for ulceration [36]. Giza et al. [37] have reported a rare case of irreversible sciatic nerve damage in an 8-year-old girl with T1D and severe ketoacidosis, despite no prior neuropathic symptoms. Although full-blown diabetic foot syndrome is rare in children, subclinical neuropathy often occurs. Pathogenic mechanisms are common to T1D and T2D, but risk factors and incidence rates differ between the two types of diabetes.

4.2.2. Diabetic neuropathy and the risk of injuries

A child with neuropathy may not feel minor injuries caused by ill-fitting shoes, which increases the risk of developing wounds and ulcerations. In children with diabetic neuropathy, deficits in vibration and temperature sensations increase the risk of not feeling injuries or pressure sores caused by ill-fitting shoes [3]. Microtraumas caused by the loss of proprioceptive sensation may lead to ulceration [38]. Chronic hyperglycemia consequent to the long-term, poorly controlled diabetes leads to angiopathy, which impairs blood circulation in the feet and increases susceptibility to infections. Five years into T1D in children and adolescents, microvascular changes manifest as a thickened capillary basement membrane, impairing microcirculation [2]. A reduction in blood flow to the feet, which may reach 40%, and impaired angiogenesis, due to the decreased production of the vascular endothelial growth factor (VEGF), obstruct oxygen delivery to wounds and the healing process [36,39]. Additionally, reduced leukocyte migration to tissues due to angiopathy increases the risks of wound contamination and infection [40]. The risk of wound healing impairment in diabetic children increases by 18% with each 1% increase in glycated hemoglobin (HbA1c) [32].

Neuropathies and tendinopathies are enhanced by the accumulation of advanced glycation end products (AGEs) in diabetes. Glycation of collagen in the tissues of the foot translates to muscle and joint weakness and gait disturbances [41]. These molecules irreversibly change collagen, disrupting its cross-linking integrity and the foot biomechanics. Moreover, AGEs induce mitochondrial dysfunction in tendon fibroblasts, which reduces ATP synthesis and cell proliferation, as confirmed in vitro models [42]. The reversibility of changes with improved glycemic control is not complete. An improvement in HbA1c by 3% reduces the skin collagen glycation by 20%. However, structural changes, like collagen cross-linking, are difficult to reverse [43]. AGEs increase the stiffness of the Achilles tendon and plantar fascia, the structural elements subjected to intense growth and physical activity in children. Studies report that Achilles tendon stiffness is higher in diabetic patients than in healthy individuals in over 50% of cases, correlating with higher plantar pressure in the forefoot [44, 45]. In children and adolescents with T1D, limited mobility of the ankle and metatarsophalangeal joints occurs in 34% of patients, which increases the risk of flat feet and calluses. Metabolic disturbances in diabetes that affect collagen structure may lead to cheiroarthropathy, characterized by tendon stiffness and limited joint mobility, further disrupting foot biomechanics. Risk of cheiroarthropathy increases by 46% with each 1% increase in HbA1c. In patients with HbA1c > 8%, a 22.5% higher pressure has been reported under the head of the 1st metatarsal bone [32, 46]. Biomechanical changes in diabetic feet manifest as a 23% to 36% limitation in ankle joint mobility, leading to a 35% increase in the midfoot pressure as noted in pedobarographic studies, which disrupts the foot roll-over phase during gait [47, 48]. Pedobarography permits an early diagnosis of threatening foot instability and initiation of glycemic control, which is crucial for combating foot complications [49]. It takes on a role corresponding to the "prayer" and "tabletop" tests used in diagnosing palm disorders [2, 50].

Charcot foot, an acquired condition due mostly to poorly controlled or undiagnosed diabetes, is a destructive joint disease of the foot associated with neuroarthropathy that develops secondary to chronic diabetic inflammation, leading to joint and bony deformities and non-healing foot ulcers. The disease develops at all ages, although it is most frequent in adulthood. AGEs and impaired bone remodeling are common pathogenetic mechanisms [48, 51]. Charcot foot is a complication associated with advanced neuropathy, occurring in 0.1% to 0.8% of diabetics. It is rare in children but possible in patients diagnosed with diabetes in childhood after decades of the disease [52]. In a cohort study, patients with T1D developed Charcot foot, on average, 24 years after the onset of diabetes, while patients with T2D developed it after 13 years. The youngest patient with Charcot neuroarthropathy was 28 years of age, with diabetes diagnosed in childhood [53]. The key factors underlying neuroarthropathy were chronic inflammation, superimposed microtraumas, long duration of diabetes (> 15–20 years), and poor glycemic control (HbA1c > 8%), all of which led to gradual bone/joint destruction.

4.2.3. Lipid disorders

Lipid disorders, often associated with obesity and diabetes, contribute to the development of atherosclerosis, which worsens blood supply to the lower extremities. In children with obesity and increased low-density lipoproteins, the arterial intima-media layer is thicker than in the normal-weight group. Such changes correlate with impaired blood flow in the lower extremities as assessed by the ankle-brachial index (ABI) [54, 55]. Studies report that adolescents with T1D and hyperlipidemia show reduced arterial reactivity, which points to potential endothelial dysfunction and increased risk of atherosclerosis. Children with obesity and elevated triglyceride levels (> 150 mg/dL) have a higher risk of developing calcifications, which impair blood flow in the posterior tibial arteries [2]. Each LDL increase by 30 mg/dL increases the risk of an ABI reduction below the cut-off level of 0.9 by 35% in adolescents with T2D, pointing to early atherosclerotic changes. Triglyceride levels > 200 mg/dL in obese children are associated with a 2-fold higher risk of stenosis in large arteries, as found in a Doppler study [53]. Thus, childhood dyslipidemias are highly prone to developing foot disorders in children. Keeping the LDL level < 100 mg/dL in children reduces the progression of atherosclerosis by 40% to 60% [56].

A study by Pappalardo et al. [2] compared the impact of obesity associated with T1D (HbA1c of 6.3% and diabetes of 5.7 years) on foot structure in children and adolescents, focusing on the plantar metatarsal fascia thickness (MFT) and the metatarsal fat pad (MFP). The assessment also included the body mass index (BMI), waist circumference (WC), waist-to-height ratio (WHR), navicular drop test—an arch flattening index, and foot-posture index (FPI-6). The findings were that MET and MFP correlated with BMI (r = 0.66; p < 0.001), WC (r = 0.68; p < 0.001), and WHR (r = 0.59; p < 0.001). Additionally, the navicular drop test correlated with WHR (r = 0.39; p = 0.009), and the MFT/MFP ratio increased significantly. These findings assert that increased metatarsal fascia thickness predisposes to the development of plantar fasciopathy, and foot destructuring is more related to excess body weight than diabetic pathology per se.

Pedobarography, supported by ultrasonography, is the most practical examination for disordered foot homeostasis caused by metabolic disturbances in childhood. It enables an objective assessment of how the feet are loaded in the conditions outlined above. Increased overall foot load, areas of excessive pressure (e.g., in the forefoot or heel), and flattening of the longitudinal and transverse arches are depicted and quantified. Children with obesity show increased foot load. Pressure is higher under the forefoot, particularly under the lateral and medial forefoot, and under the 2nd to 5th metatarsals. An increased thickness of the metatarsal fat pad adds to plantar pressure redistribution [57]. The higher dynamic peak pressure and force that develop in overweight preschool-aged children under the mid-foot and metatarsal bones lower the longitudinal and transverse arches, expressed by lower footprint angles, compared to their peers with normal body weight. The arch flattening results from structural changes in the foot, in addition to and beyond the effect of a thickened fat pad [58]. Additionally, reduced foot sensitivity increases the risk of injuries and threatening infections [40, 59]. The increased overall plantar load and pressure values are like those noted in obese adults [60].

In children with diabetic neuropathy, abnormal pressure distribution resulting from sensory disturbances and biomechanical changes highlights the areas at risk of ulceration. Twenty-three percent of children with T1D have subclinical sensory disturbances, which increase the risk of mechanical injuries and show abnormal pressure distribution in pedobarographic examinations. The 1st metatarsal bones of the forefoot and midfoot are the particular risk areas, since these are the sites of increased plantar pressure and foot contact area [32]. Inadequate glycemic control, as assessed by HbA1c, increases the risk of neuropathy. Forty percent of pediatric patients with T1D have symptomatic or symptomless peripheral neuropathy, accompanied by higher pressure under the forefoot and prolonged stance time [51]. Obesity alone, with the BMI > 90th percentile, increases the risk of neuropathy and biomechanical overload [61]. Obesity overlapping the T1D flattens out the longitudinal foot arch and increases the midfoot pressure, predisposing to ulcerations. A WHR higher than 0.5 correlates with increased under-heel pressure and foot distortion [2]. Aside from routine monofilament and vibration testing, a pedobarographic examination is key for early detection of zones with sensory impairment that generate excessive plantar pressure, preceding the full-fledged clinical changes [44].

4.2.4. Perspective for clinical practice

Effective management of T2D needs a paradigm shift from the pharmacotherapeutic model to an integrated, multidisciplinary system of community-based nurse-led care, the Lifestyle Medicine Case Manager Nurse (LMCMN) [62,63]. A meta-analysis of randomized controlled trials has shown that individualized preventive and therapeutic nurse-led support gives clinically significant reductions in HbA1c by an average of 0.42 [64]. The LMCMN emphasizes a holistic perspective on mutually interconnected rather than isolated elements, also including the patient's motivation and aptitude for coping with the disease. The nurse plays a pivotal role in addressing the patient's medical, educational, and emotional barriers. This role includes knowledge of predictive and diagnostic tools. The application of artificial intelligence (AI) enables the creation of personalized predictive models for the risk of complications, for instance, based on data from continuous glucose monitoring systems [65], while techniques such as pedobarography allow for the early detection and prevention of diabetic foot by analyzing plantar pressure distribution [66]. Equipping the LMCMN with proficiency in these technologies maximizes the effectiveness of the entire therapeutic process.

4.3. Foot homeostatic and regulatory aspects

Metabolic dysregulations underlain by dyslipidemia, diabetes, and obesity have overlapping cellular and molecular characteristics, mostly underlain by proinflammatory and hypoxic propensity. Hyperglycemia and hyperlipidemia inhibit hypoxia-inducible factor (HIF-1α) activation in response to tissue hypoxia by prolyl hydroxylase-dependent and independent mechanisms. HIV-1α is the master regulator of oxygen homeostasis, which induces the expression of target genes to keep cellular oxygen homeostasis. HIF-1α destabilization shifts the redox signaling pathway toward a prooxidant state, which has progressively free-radical-related damaging effects on the structural, soft, and bony tissues of body systems, of which the foot is no exception [67].

Fibroblasts, richly represented in foot tissues, are the cells that have been drawing increasing attention. Contrary to the former views of fibroblast functional neutrality, these cells are engaged in tissue homeostatic integrity and healing activity, particularly in the presence of injury and ulceration, common diabetic complications, and the causes of hard-to-treat morbidity [68]. Restoration of cellular homeostasis is crucial for wound healing. Knowledge of the underlying mechanisms of wound healing has recently advanced with the understanding of the role of nuclear factor erythroid 2-related factor 2 (Nrf2), a redox-sensitive transcription factor. Nrf2 is a crucial regulator of intracellular redox homeostasis, influential for the expression of genes that regulate the production of free radical scavengers and thereby decrease oxidative tissue stress [69]. The child's foot, particularly during the gait and walking developmental period, is vulnerable to metabolically induced disruptions in fibroblast functions and the tendon-to-muscle attachment [70]. Dysfunction of biomechanical bridging, generating force due to muscle contraction, impacts foot shape and contact pressure with the ground. The collagen-based structures underlying joint mobility are also affected, which translates to dysfunction of the foot-brain axis.

The concept of the foot-brain axis refers to the fundamental role of the foot as a sensory organ, supplying the brain with proprioceptive (body position in space) and exteroceptive (contact with the ground) inputs. Plantar sensation is crucial to sustaining body balance, postural control, and gait coordination. Mechanoreceptors found in the foot sole provide information about pressure and skin deformation, which is integrated by the brain and translated into its neural output [38]. Impaired tactile signals from foot proprioceptors, entering the sensory cortex and the anterior cingulate cortex, distort the function of the central posture controller [71, 72]. The action of this controller is aided by proprioceptors in foot muscle fibers, like the extensor digitorum brevis muscle, which provides information about the ankle joint position [73, 74]. The feedback-operating foot-brain signal processing is dysfunctional in perceptive deficits associated with metabolic disorders. Changes in plantar pressure distribution patterns in childhood lead to distant distortions of the neuromuscular foot-brain axis in adulthood.

The literature reviewed above consistently shows that pedobarography is a useful, if not sometimes essential, tool for diagnostic and managerial interventions in the foot abnormalities of childhood. This tool, capable of mapping every square centimeter of the plantar surface, has a standing use in orthopedics and related genetic and acquired disorders, not the least of which is the choice of proper corrective footwear [6, 75, 76]. Pedobarography is poised to become a quantitative assessment tool for the child's foot in metabolic disturbances.

4.4. Limitations

This review has limitations. Literature research has an inherent bias linked to the choice of search keywords and their combinations. The assessor's appraisal of the literature depends, to an extent, on the specific nuance he wants to convey, which, in turn, is influenced by his research and clinical interests. Likewise, judging the merit and quality of publications may vary, particularly in a review like the present one, where a broad palette of different clinical entities was the subject of analysis and interpretation. The foot ontology appears not to be independent of how the researcher perceives and conceptualizes the nature of the foot-brain axis in the child's development. We mitigated these biases by applying stringent boundaries for the literature search and relevance criteria for the papers found, which helped focus on conveying the meaning and significance of contributions. Despite these limitations, we believe we have shown the role of pedobarography as a biomarker of children's foot homeostasis and the need for proper foot care to avoid the progression of foot-brain axis dysregulation to clinical disorders.

5. Conclusions

Childhood is a time of rapid development, growth, and the use of feet. The foot is a complex, multi-structural organ that coordinates a proprioceptively driven system to sustain body movements, balance, and weight-bearing functions, signaling the brain controller the need for momentary changes to sustain motion coordination. The foot-brain axis is distorted by general metabolic (via neuropathy) and structural (obesity) disorders, increasingly frequent ailments developing at an early age. Studies show that abnormal plantar pressure distribution in children with metabolic-driven diabetic and lipid disorders is mostly concentrated in the forefoot (metatarsal heads) and midfoot. These changes result from the loss of foot sensations and biomechanical dysfunction. In the longer term, the skewed foot-to-brain signaling reaching the brain controller bounces back, worsening body balance and gait pattern, which increases the risks of falls and further injuries.

Pedobarography is an outstanding diagnostic tool to quantify the functional consequences of dysregulated foot homeostatic pathways in metabolic disorders. It provides objective, dynamic data on plantar pressure distribution. This method can translate diagnostic data into direct therapeutic interventions, transforming passive monitoring into proactive regulation of biomechanical homeostasis. It aids in planning targeted surgical corrective procedures when conservative treatment fails. It helps restore the proprioceptive feedback loop of the foot-brain axis, dysregulated in metabolic neuropathies and neuromotor disorders, thereby enhancing the effectiveness of kinesitherapy. The translational aspects of pedobarography also lie in the development of wearable technologies, such as custom-made footwear or orthoses that target specific areas of pathological loading and sensor-equipped insoles that can monitor and autonomously correct increases in plantar pressure, thereby having a preventive role against worsening dysregulation. The use of pedobarography also informs public health policy about the need to classify patients with abnormal plantar pressure and metabolic disorders, even those biomechanically asymptomatic, into the risk groups that should be subject to more tenacious metabolic control to protect foot health. A broad role and the ability of pedobarography to quantify dysfunctional changes make it a potential biomarker of homeostatic disruption of pediatric foot health.

Future research should focus on integrating molecular-level interventions with the functional capabilities of pedobarography. Studies should be designed to target pathophysiological regulators, such as advanced glycation products in hyperglycemia or inflammatory molecular indices with dysregulated foot biomechanics. In this paradigm, pedobarography would not only serve as a diagnostic tool but also become a quantifiable, objective verifier of whether a biochemical intervention has translated into an improvement in gait dynamics and the desired reduction in pathological loading. A review of pedobarography-related literature gives a consistent impression that the method's role in managing pediatric disorders of the musculoskeletal axis, starting from the feet upwards, still awaits further exploration.

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