How body mass affects foot structure and arch development in primary-school aged children

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Abstract

Introduction: Childhood obesity has long been associated with long term health consequences including musculoskeletal issues. Deviations from the normal foot structure can greatly compromise foot function, causing discomfort and pain. No research has yet examined the feet of primary-school aged children during the critical stage of arch development. The aim of this study was to examine the feet of primary school aged children in terms of foot types and soft tissue structure and how body mass can affect the arch development in young children.

Methods: Thirty-nine primary school aged children (mean age, 5.58± 0.67 years) participated in this study. Foot types were determined via footprint analysis with scanned images of the sole of the feet, using the Chippaux-Smirak index. Thickness of the fat pad, plantar fascia as well as cross-sectional areas of the flexor digitorum brevis and flexor hallucis brevis were measured via ultrasound. Soft tissue structures that had the biggest influence on arch flexibility were the flexor hallucis brevis, proximal plantar fascia, and flexor digitorum brevis cross-sectional area when normalised to body mass.

Results: Significant differences of foot types between normal weight, overweight and obese children during sitting and standing were found ($p=0.009$ and $p=0.006$ respectively). The majority of overweight and obese children were classified with having a pes planus foot type. Overweight and obese children also tend to have more flexible feet compared to normal weight children. When normalised to lean body mass and body mass, all soft tissue structures showed significant differences between the different weight classes.

Conclusion: The feet of overweight and obese children tend to be flatter and more flexible compared to normal weight children. As body fat percentage increased the size of the soft tissue structures increased in absolute terms but decreased once normalised to body mass. Therefore, soft tissue structures in overweight and obese children are unable to carry the extra load causing the collapse of the medial longitudinal arch. As these soft tissue structures are vital in forming the medial longitudinal arch, early strengthening programs could prevent symptoms later in life.

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Foot anatomy

Over 5 million years, the modern human foot has evolved into its current structure and functioning (1). The foot was used for climbing tasks until bipedalism first appeared 3-4 million years ago, whereby the anatomy and function of the foot dramatically changed (1, 2). The human foot is a complex structure with 26 bones, more than 30 joints, over 100 ligaments, 13 extrinsic and 21 intrinsic muscles (2-5). The foot is the only component of the human body that is in contact with the ground and plays a crucial role in minimising ground impacts, maintaining stability during walking, transmitting as well as generating power during walking and acting as a general lever for propulsion (1, 3). The entire foot and ankle complex consists of 6 independently functional segments which include the shank, rearfoot, midfoot, lateral forefoot and medial forefoot (1). Each of these segments behave differently depending on the type of locomotion, speed, and active and passive coupling mechanisms within each foot segment (1).

Bones and joints

Forefoot

The forefoot consists of five metatarsal bones and fourteen phalanges (6). The medial forefoot consists of the first metatarsal and tarsometatarsal joints as well as the first proximal and distal phalanges, which form the hallux and the interphalangeal joint. The medial forefoot functions as a pillar and forms the distal truss of the medial longitudinal arch (1). The lateral forefoot consists of the remaining four metatarsals and the lesser toes. The bases of the five metatarsal bones articulate to create four intermetatarsal gliding joints. The heads of the five metatarsals articulate with the bases of the five proximal phalanges to create five metatarsophalangeal joints. Movements at the metatarsophalangeal joints include flexion, extension, abduction and adduction. Articulations between the phalanges create the interphalangeal joints, which include the distal and proximal interphalangeal joints only permitting flexion and extension. The hallux is the only toe to lack a middle phalanx (7), and thus only has one interphalangeal joint. Joint capsules as well as medial and lateral collateral ligaments provide stability for the metatarsophalangeal and interphalangeal joints (1).

Midfoot

The midfoot consists of the navicular, cuboid and the three cuneiform bones, which are also known as tarsal or short bones. The cuboid is located just laterally and anteriorly to the calcaneus, with the navicular situated medially from the cuboid. The three cuneiforms (medial, intermediate, and lateral) are located distally to the navicular (7). The talonavicular and calcaneuocuboid joints connect the midfoot with the rearfoot. The distal tarsal bones form further gliding joints including the cuneonavicular joints, cuboideonavilar joint, intercuneiform joints and cuneocuboid complex (6). The medial, lateral, and transverse longitudinal arches are formed by the bones of the midfoot. The function of these arches is to transmit as well as attenuate forces during locomotion (1).

Rearfoot

The rearfoot consist of short bones, also known as tarsal bones, which include the talus and calcaneus (1, 6, 7). These bones articulate at the intertarsal joints of the foot, which are considered gliding joints (7). The talus bone is an unusual bone in that it does not have any direct muscular attachments, but instead relies on the forces applied to it by the joint articulations with the calcaneus and navicular (8). The talus articulates with the calcaneus to create the subtalar joint. The anterior talocalcaneal articulation and posterior talocalcaneal articulation of the subtalar joint are separated by the tarsal canal. Supination and pronation are the primary osteokinematic motions of the subtalar joint. The calcaneus is the largest tarsal bone and also sustains the largest impact forces during heel contact in locomotion (8). The calcaneus provides a long moment arm for the achilles tendon, which can sustain large tensile forces and helps transmit the weight of the body from the rearfoot to the forefoot (8). The ankle joint itself is formed by the two bones of the shank (i.e. tibia, fibula) and the talus allowing for plantarflexion, dorsiflexion, eversion and inversion (6, 8).

Muscles

Extrinsic muscles

The extrinsic muscles of the foot are larger muscles that run along the posterior, anterior and lateral aspects of the shank and all attach to the dorsal aspect of the foot. The tibia and fibula and the interosseous membrane separate the extrinsic muscles into anterior, posterior, and lateral muscle groups. The extrinsic muscles are responsible for the bigger foot and ankle motions such as plantarflexion, dorsiflexion, eversion and inversion (1).

Anterior group

The anterior muscle group consists of the tibialis anterior, extensor digitorum longus, extensor hallucis longus and the peroneus tertius. The tibialis anterior, extensor digitorum longus and extensor hallucis longus all originate at the proximal half of the tibia and interosseous membrane. The peroneus tertius originates at the distal anterior surface of the fibular as well as the interosseous membrane. The peroneus tertius is the smallest muscle of the anterior compartment and inserts at the dorsal surface of the fifth metatarsal. Its actions include dorsiflexion and eversion of the foot. The extensor hallucis longus inserts at the dorsal aspect of the distal phalanx of the hallux. It also assists with dorsiflexion of the foot but primarily extends the hallux (1, 9). The extensor digitorum longus inserts at the 2^{nd} to 5^{th} proximal phalanges and proximally at the base of the 5^{th} metatarsal. The extensor digitorum longus will work with the tibialis anterior to dorsiflex and supinate the foot but its primary role is to extend the phalanges (1). The tibialis anterior is the largest muscle of the anterior compartment. It inserts on the inferomedial aspect of the medial cuneiform and the base of the first metatarsal and its function is to dorsiflex and supinate the foot. The tibialis anterior is also responsible for maintaining balance during gait, particularly during the first quarter of the stance phase (1, 9).

Lateral group

The lateral compartment consists of the peroneus (fibularis) brevis and peroneus (fibularis) longus. The peroneus brevis originates at the lower two thirds of the lateral shaft of the fibula and inserts at the tuberosity of the base of the 5^{th} metatarsal. It functions as primary evertor of the rearfoot and midfoot. The peroneus longus originates at the head of the fibula and superior tibiofibular joint and inserts at the base of the first metatarsal and medial cuneiform. It is an important muscle for the stabilisation of the midfoot and responsible for eversion of the foot.

Posterior group

The superficial posterior muscle group consists of the gastrocnemius and soleus; together they are also known as triceps surae. The gastrocnemius originates at the medial and lateral condyles of the femur while the soleus originates at the middle third of the posterior border of the tibia and proximally at the posterior shaft of the fibula. Both muscles insert at the calcaneal tuberosity. During stance, these muscles control the forward progression of the shank and talus and also assist with flexion of the knee. The triceps surae also have the ability to apply tension to the plantar aponeurosis (plantar fascia) and thus mechanically influence the rear-, mid- and fore-foot function (1).

The deep posterior muscle compartment consists of the flexor hallucis longus, flexor digitorum longus and tibialis posterior. The flexor hallucis longus originates at the lower two thirds of posterior aspect of the fibula and inserts at the base of the distal phalanx of the hallux. It is able to flex the distal phalanx of the hallux and provides support for the medial longitudinal arch. The flexor digitorum longus originates at the posterior shaft of the tibia and inserts at the base of the distal 2^{nd} -5^{th} phalanges. Its function is to flex the distal phalanges as well as providing support for the lateral longitudinal arch (1, 9). Both muscles support the longitudinal arches by contracting isometrically during the stance phase. The tibialis posterior originates at the proximal two-thirds of the posterior surfaces of the tibia and the fibula and interosseous membrane. It inserts at the navicular and medical cuneiform bone. It functions as an invertor and plantar flexor of the foot and ankle (1).

Intrinsic muscles

First Layer

The intrinsic muscles of the foot are located on the plantar aspect of the foot and are separated into four distinct layers. The first superficial layer includes the abductor digiti minimi, flexor digitorum brevis, and abductor hallucis. All three muscles originate at the medial tubercle of the calcaneus, while the abductor digiti minimi also originates from the lateral tubercles. The abductor digiti minimi inserts on the lateral base of the fifth proximal phalanx and abducts the fifth phalanx. The flexor digitorum brevis inserts on the middle phalanx of the 2nd – 5th digits and flexes the phalanges. The abductor hallucis inserts on the medial base of the first phalanx of the hallux.

Second layer

The second plantar layer consists of the quadratus plantae and lumbrical muscles. Both muscles attach to the tendon of the flexor digitorum longus and function with the flexor digitorum longus to flex the toes. Additionally, the lumbrical muscles extend the toes at the interphalangeal joints (9).

Third layer

The third plantar layer includes the flexor digiti minimi, adductor hallucis and flexor hallucis brevis. The flexor digiti minimi originates on the base of the 5th metatarsal and inserts on the base of the fifth proximal phalanx. The adductor hallucis has two heads, the oblique and transverse head. The oblique head originates on the base of the 2nd through to 4th metatarsal and inserts on the base of the first proximal phalanx. The transverse head originates laterally on the plantar metatarsophalangeal ligaments and inserts together with the oblique head on the base of the first proximal phalanx. The flexor hallucis brevis originates on the cuboid, lateral, middle and medial cuneiform and inserts on the base of the first proximal phalanx. The flexor digiti minimi, adductor hallucis and flexor hallucis brevis flex the 5th phalanx, adduct the hallux, and flex the hallux, respectively. During the loading of the forefoot in the latter half of the stance phase, the flexor hallucis brevis and the flexor digiti minimi help to stabilise the forefoot and eccentrically control toe extension from mid-stance to swing phase (9).

Fourth layer

The fourth and deepest plantar layer contains the three plantar interossei. The planter interossei originate proximally on the medial shafts of the 3rd to 5th metatarsals and insert on the bases of the articulating proximal phalanges. These muscles are able to adduct the toes and help to stabilise the forefoot during forefoot loading by providing isometric and eccentric control of the toes (9).

Arch development

Anatomy of the arch

The foot has three arches – the transverse arch, lateral longitudinal arch, and the medial longitudinal arch. All three arches are formed by the tarsal and metatarsal bones, which are strengthened and supported by ligaments, tendons, and muscles. The transverse arch is formed by the bases of the metatarsal bones, the cuboid and the three cuneiform bones (1). The height of the transverse arch can be increased by synergetic contraction of peroneus longus and brevis and flexor digitorum longus muscles. The lateral longitudinal arch is formed by the calcaneus, the cuboid, and the fourth and fifth metatarsals. Together with the tendon of the flexor digitorum longus, the peroneus longus and brevis tendons help to contribute to support the functioning of the lateral longitudinal arch. Synergistic contraction between those muscles and the flexor digitorum longus can increase the height of the lateral longitudinal arch and also contribute to force attenuation and stabilisation of the transverse and lateral longitudinal arches (1, 9). The flexor digitorum longus and flexor hallucis longus support both longitudinal arches by contracting isometrically during the stance phase (1). The medial longitudinal arch is the highest arch of the foot. It is formed by the calcaneus, the talus, the navicular, the three cuneiforms, and the first, second, and third metatarsals. It is supported by peroneus longus and brevis, flexor digitorum longus, flexor hallucis longus, flexor digitorum longus, abductor hallucis, and abductor digiti minimi (1). Additionally, the abductor hallucis and abductor digiti minimi contribute to the stabilisation and eccentric control of the arch descent during loading (9).

Primary function of the arches

The development of the human arch is considered to be the primary step in evolution of the bipedal human gait (10). The transverse and longitudinal arches essentially act as a link between the fore and hindfoot and the medial and lateral forefoot (11). They are also critically important to weight transfer, as they have the capacity to modify force attenuation during contact, thus ensuring safe loading during weight bearing (11, 12). The function of a foot is dependent on its morphological structure and regular shape of the longitudinal and transverse arches (13). The medial longitudinal arch as well as the transverse arch are both crucial in providing stability and resiliency to the loaded foot, while the medial longitudinal arch is considered to be primary load bearing and shock absorbing structure of the foot (6). The medial longitudinal arch helps to provide the plantarflexors with enough mechanical advantage to propel body weight during stance and provide the foot with the capacity to absorb shock caused by upright standing (10).

Arch development during childhood

In the prenatal period the foot is composed of growing cartilage which are commonly dome or rectangular in shape (12). The ossification process of the bones already begins during the 3rd month in pregnancy and at the time of birth is 30% complete and finishes by the end of the growing period of the foot (11, 12). During the first year of life the foot undergoes the fastest growing period, whereby it grows more than 4.5cm in length and nearly half their adult size (12). After the age of three years the speed of growth slows down and remains similar until puberty, but due to the slow ossification process and rapid growth after birth, the foot is prone to physical disorders (12).

The human medial longitudinal arch is not present at birth but consist of fatty tissue (14). The medial longitudinal arch develops during the first decade in life and most rapidly until the age of six years (11, 14-18). The preschool age is also a time of intensive postural body changes, whereby the medial longitudinal arch increases in height (18). General configuration of the arch is determined by the age of a child as well genetic factors (14). By the time a child starts walking, the medial longitudinal arch might be present during non-weight bearing but commonly disappears while weight bearing (14). The majority of studies agree that changes in the arch are less apparent after the age of six years and should reach the same structure as that of an adult (15, 16). As the arch becomes fully developed children also display more mature walking patterns (11). Identifying the age range during arch development in children is critical to diagnose any foot defects, as early treatment could prevent later symptoms in life (17, 18).

Bony and soft tissue importance of arch development

It was initially believed that only one particular muscle was chiefly responsible for the development of the longitudinal arch in the human foot (9). However, recent research (9) has established that arch development is a combined product of external and internal factors such as the action of gravity as well as propulsive effort of intrinsic and extrinsic muscles of the foot (9). The main bones that contribute structurally to the medial longitudinal arch include the calcaneus, talus, navicular, cuneiforms and the three associated medial metatarsals (6). The arch is additionally supported by soft tissues, the plantar fat pad and the superficial plantar fascia. Researchers still argue about how much active muscular support is actually required in order to maintain a healthy shape of an arch. In order to maintain normal arch height during weight bearing, muscle activity is required, however active support is considered to be small compared to the passive support provided by the connective tissue. The passive support mechanism of the medial longitudinal arch consists of the talonavicular joint and the associated connective tissue, which forms the keystone of the arch. The plantar fascia, spring ligaments, and first tarsometatarsal joint are responsible for maintaining arch height and general shape. The plantar fascia, a dense connective tissue that covers the sole and sides of the foot, provides the primary passive support to the medial longitudinal arch and is capable of resisting up to 810N of tension before permanent deformation (6). During standing, body weight is generally applied through the foot near the talonavicular joint and the load is then distributed anteriorly and posteriorly throughout the medial longitudinal arch, passing to the fat pads and thick dermis over the heel (6). Body weight pushes the talus slightly inferiorly, causing the arch to lower slightly. As the arch drops, the distance between the calcaneus and metatarsal heads increases. The tension in the stretched connective tissue act as a semi-elastic tie that gives slightly under the load allowing the slight drop in the arch. Research in cadavers also indicated that the deep plantar fascia the major structure that maintains the height of the medial longitudinal arch (6). Active muscles are only considered to be a secondary line of support.

Foot types

Differences in foot types and causes

Human feet are often classified into one of three different foot types: pes planus (ie flat arch), pes rectus (ie normal arch) and pes cavus (ie high arch) feet (19). Foot types are considered to be morphological descriptions of the feet that combine arch height and structural differences in alignment (19). Thus, the clinical concept of foot types helps to simplify the anatomical complexities of the human foot (5). Interpretation and measurements for defining foot types are clinically more practical and cost effective than examining foot function (5, 19). Pes rectus, pes planus, or pes cavus classifications are often based on the height of the medial longitudinal arch, using one of several available methods (13). The most popular method is the indirect method of using footprint analysis (16). It is a simple method based on measures of the surface area of the foot when in contact with the ground, which allows for categorisation of feet according to the height of the medial longitudinal arch as either high, normal, intermediary or low. The height of the arch can then be assessed via different anthropometric measurements, such as the footprint angle and Chippaux Smirak index. Arch height can also be assessed with direct measures including radiographs, which is considered to be a reliable method to assess foot structure during weight bearing. The talus – first metatarsal angle is described as the most consistently accurate radiographic parameter of a pes planus, pes rectus, and pes cavus foot type (13).

Different foot types can result from a variety of factors including altered bone shape and/or position, soft tissue injuries or failure, as well as muscle imbalances or injuries (20). Yet, the general association between foot type and clinical disorders is poorly defined. It is estimated that around 5-10% of the population have pes cavus foot type while 3-19% have been classified as pes planus. Both foot types have been known to cause long term pain and can lead to deficits in balance and mobility as well as developing lower extremity injury (21). Conversely, pes rectus feet are considered normally aligned and have no direct association of pathology or injury (5, 20).

Pes Planus

A pes planus foot is generally characterised by an abnormally dropped medial longitudinal arch (6, 22) and is believed to affect around 2-25% of the adult population globally (23, 24). Pes planus feet overpronate, thus causing the ground reaction forces to travel medially through the stance phase (5).The drop in the medial longitudinal arch is often considered the result of laxity within the joints of the midfoot or proximal forefoot commonly combined with a weak, overstretched, or torn plantar fascia, spring ligament and tibialis posterior tendon. As the arch of the foot collapses, the subtalar joint becomes excessively pronated, the forefoot is slightly abducted, and the rearfoot everted (6, 13, 23)

Possible causes of pes planus feet

A high body mass index, obesity, hypertension, improper development, trauma, and degenerative processes of aging are considered to play a factor in the development of pes planus foot type (13, 20). Mechanisms for the development of pes planus also include a complex interaction between the external ground reaction forces and internal forces in ligaments, joint capsules, and intrinsic and extrinsic muscle tendon units (23). Intrinsic factors for a collapsed arch include excessive tension in triceps surae muscles and relative weak tibialis anterior, extensor digitorum longus, and extensor hallucis longus muscles (13).

Associated symptoms

People who have a moderate or even severe form of pes planus have a compromised ability to support and dissipate loads through the foot (6). A pes planus foot type may contribute to injuries due to the altered motion of the lower extremities (21). Lower extremity injuries can include metatarsal stress fractures, plantar fasciitis, achilles tendinitis, tibialis anterior inflammation and patella- femoral joint pain (25). Individuals with pes planus foot type are more susceptible to tissue stress injuries compared to those with pes cavus foot type as pes planus foot type have greater foot mobility (21). People exhibiting pes planus foot type also have higher odds of hallux valgus and hallux rigidus, which are lateral deviation of the hallux and stiffness of the hallux respectively (5, 24).

The role of foot muscles

The abductor hallucis, flexor digitorum brevis, and plantar fascia each contribute to supporting the medial longitudinal arch (23). The abductor hallucis is a dynamic elevator for the medial longitudinal arch and when weakened lowers the medial arch height. It is not uncommon for people with pes planus feet to complain of plantar fasciitis, whereby the plantar fascia thickens. It is believed that the plantar fascia has to bear greater loads and adapts by becoming thicker and stiffer as a result (23). Extrinsic muscles also play an important role in forming the arch. In order to compensate for the lack of tension provided by the connective tissue in an asymptomatic pes planus foot type, intrinsic and extrinsic muscles of the foot require a significant amount of active forces (6). Extrinsic muscles, such as the peroneus longus and tibialis anterior are highly active during standing to compensate for the inadequate skeletal framework and support the medial longitudinal arch (25).

Asymptomatic versus symptomatic pes planus

Pes planus foot type is further classified as asympotomatic or symptomatic feet. Asymptomatic feet are considered flat but pain free, while symptomatic feet commonly present pain near the medial malleolus and medial arch. It is not yet understood why some people experience symptoms and why some do not(20). Some researchers define the asymptomatic pes planus foot as a flexible flatfoot, whereby the medial longitudinal arch maintains a normal structure during non-weight bearing but collapses during weight bearing. The collapse of the arch during weight-bearing is not associated with any discomfort (26).

There is a disagreement in the literature as to whether asymptomatic pes planus foot type requires treatment (22). Some researchers believe that pes planus is a physiologically normal foot type in infants, children and even some adults; however other researchers hypothesise that persistent pes planus foot type in children can actually lead to disabilities in adulthood. A pes planus foot type can also be acquired in adulthood and commonly presents with a vague pain in the medial foot behind the medial malleolus. As individuals age, the shape of the foot will change, resulting in rigidity and arthritic changes (22).

Pes Cavus

A pes cavus foot type is characterised by a raised medial longitudinal arch that is structurally rigid and thus a poor shock absorber (27, 28). It is estimated that about 8-15% of the global population is affected by pes cavus foot type; of those exhibiting a high arch, around 60% suffer from pain and discomfort. In a pes cavus foot type the calcaneus is commonly in a vertical pitch of more than 30 degrees, with toes retracted and the forefoot and first metatarsal often flexed and adducted (20, 27, 28). These deformations result in lower plantar pressure at the medial arch and increased plantar pressure at the heel and forefoot (21). While the medial longitudinal arches of pes rectus and pes planus foot types slightly collapse during weight bearing, the arch associated with a pes cavus foot type often does not flatten during weight bearing (28). The rigidity and reduced shock attenuation combined with increased peak plantar pressure are the most common causes for foot injury related issues in pes cavus feet (21).

Possible causes of pes cavus feet

There are several causes for pes cavus feet which can be from neurological impairments or secondary to neurological impairments (28). Early development (before the age of 10 years) of a pes cavus foot type is often from combination of neurological impairments and growth-related changes. For example paralysis of the toe extensors and/or the triceps surae can contribute to a direct pes cavus deformity (29). Secondary causes can be from general muscle imbalances and a weak gastrocnemius-soleus muscles complex (4, 28). Non-neurological causes are considered to be rare but can include skeletal dysplasia syndromes, birth defects, progression of congenital idiopathic clubfoot and trauma (29).

Associated symptoms

While pes cavus foot type can be asymptomatic for some people, most people can be severely affected and problems tend to arise from 5-20 years of age (20, 28). As the height of the medial longitudinal arch is increased, the distance between the calcaneus and metatarsals is shortened (4, 6). This shortening, as well as an overload of the metatarsal heads, often causes metatasalgia and sesamoiditis, which induce pain and inflammation at the base of the proximal phalanges. As the medial longitudinal arch is raised, the contact area of the foot with the ground becomes smaller. The diminished contact area often results in plantar heel pain and general instability of the rearfoot, which is reinforced by weak dynamic stabilizers including a weak peroneus brevis (27, 28).

The role of foot muscles

Muscular imbalances that stem from neurological disorders have long been considered to be the primary factors of a pes cavus deformity. General muscle imbalances include higher strength in inverter muscles compared to everter muscles, and higher strength in plantarflexor compared to dorsiflexor muscles (30). Frequent muscle imbalances also include normal muscle strength of the peroneus longus and tibialis posterior muscles, while their respective antagonist muscles, the tibialis anterior and peroneus brevis have decreased strength. This muscle imbalance causes a functional overpull, resulting in increased arch height (30). Neurological disorders of the central nervous system can cause an overpull of the Achilles tendon, tibialis anterior, flexor hallucis longus, and flexor digitorum longus, which in turn contributes to a pes cavus foot type (30). Thus, a variety of muscular imbalances can contribute to a pes cavus deformity.

Childhood obesity and the influence on foot structure and function

Obesity and overweight has reached epidemic levels in many developed countries and is considered to be the most serious health problem and most common chronic illness of the 21st century (4, 31, 32). The past few decades have seen a great increase of overweight and obese children worldwide; it is estimated that there are around 20% overweight and obese children in Europe, and around 14% in other developed countries (33, 34). Childhood obesity has long been associated with long term health consequences and musculoskeletal issues, which include misalignment of the lower limbs and pain and discomfort (26, 31). Children and adolescents are growing rapidly and when obese or overweight, it can have a negative impact on the normal development of their bones, muscles and joints (35). In fact, children are particularly susceptible to obesity related musculoskeletal issues during the growth phase, which is most intense during the pre-school age (26).

Childhood obesity has great detrimental impact on the biomechanical parameters of children's gait (35). Obese children tend to have longer gait cycles, a longer stance phase duration and reduced cadence, which are issues mostly related to remaining balanced during gait (35). In the lower extremities, the feet are exposed to the additional mass in everyday life. During standing, human feet have to tolerate around 0.5 times of the body mass, while during walking and running it can be as high 1.2 times and 2-3 times, respectively (33); these levels are only exacerbated in individuals carrying excess mass. General foot structure can be affected by excess body weight at an early age of 3-5 years (32, 36). Foot pathologies and injuries in overweight and obese children are common due to the increased loading (34).

Overall foot dimensions of overweight children, including foot breadth and circumference are usually larger than those of normal weight children, although studies have struggled to differentiate between bone structure or adipose tissue in these measurements (31, 32). The most frequent condition seen in feet of overweight and obese children is a pes planus, or flattened arch, foot type (31, 33). Several studies report a lower foot print angle and higher chippaux smirak index in overweight children (31). The excess body weight causes changes in the plantar arch by changes in the osseous and ligamentous support, thus collapsing the medial longitudinal arch (31, 32). Studies have also revealed that there are no significant differences of plantar fat pad thickness between obese and non-obese children, meaning that a flatter arch as commonly seen in obese children may indeed be caused by structural changes of the foot (37). A study by Shultz et al (38) confirmed that compared to non-obese children, obese children had a significantly greater arch drop and a trend towards a more flexible arch. A significantly greater arch drop in obese children indicates that obese children have more flexible feet compared to non-obese children, which is ultimately the result of the excess weight. The lower longitudinal arch and lower mean arch height in overweight children is often associated with a decrease in integrity of the foot as a weight bearing structure (32). Some studies even reported that obese children were 3.5 times more likely to suffer from pes planus feet compared to normal weight children (39). Although there are not many reports on the long term loading effects on the developing medial longitudinal arch of growing children, it is clear that the continued pressure on the arch experienced by overweight children is causing the collapse of the arch and thus pes planus foot type (39).

The medial longitudinal arch is major factor influencing foot shape and thus great changes in foot function are also seen in overweight children (26). During static conditions, obese children display higher loading on the foot compared to non-obese children (33). Similarity, higher plantar pressures during walking in overweight and obese children have been reported (33, 36, 40). Some studies even report that the medial longitudinal arch in overweight children is most affected by the increased body weight and experiences three times higher peak plantar pressure compared to normal weight children (33). These higher plantar pressures describe the potential damaging effects of increased load on plantar tissues (36). The increased stress on the soft tissues and joints directly correlate with reduced physical activity and more time spend in sedentary behaviour, most likely due to foot pain and discomfort (33, 36). The increased plantar foot pressure in heel, midfoot, and forefoot areas of overweight children also increases the risk of lower extremity ulceration and stress fractures (39, 41).

Conclusion

To conclude, this review has explored the overall foot anatomy, foot and arch development, different foot types and their causes, as well as the impact childhood obesity can have on foot structure and function. The human foot consists of 26 bones and more than one hundred muscles, ligaments, and tendons. The bony structure of the foot can be divided into the forefoot, midfoot, and rearfoot compartments. The muscles of the foot can be divided into two major groups, the extrinsic muscle group and intrinsic muscle group. The extrinsic muscle group consists of an anterior, lateral, and posterior group. The extrinsic muscles are responsible for the bigger foot and ankle motions. The intrinsic muscles can be divided into four layers, with the first layer being the most superficial one and the fourth layer being the deepest foot muscle group. Intrinsic muscles are smaller muscles which are responsible for the finer foot and toe movements. Both extrinsic and intrinsic muscles play an important role in shaping and stabilising the foot arches. The primary functions of the arches are to help with weight transfer during gait, providing stability and resiliency, and being the primary load bearing and shock absorbing structures of the foot. Different foot types are ultimately a result of different arch heights of the medial longitudinal arch. While a pes planus foot type is a result of a low or flat arch, a pes cavus foot type is a result of a high arch, and a pes rectus foot type is considered to be a normal arch height. Several factors can contribute to a pes planus foot type, which can include a high body mass index, obesity, hypertension and improper development. Causes for a pes cavus foot type are generally considered to neurological. Both foot types can cause long term symptoms, including pain. Childhood obesity has shown to greatly influence general foot structure. Overweight and obese children tend to show larger foot breadth and circumferences and flatter feet. The additional body mass causes the plantar arch to collapse, as the osseous and ligamentous support becomes weaker. There is still a lack of literature examining the long-term loading effects on the developing arches of growing children. No research so far has yet examined foot structures and function of the feet of young children who are in the critical age of arch development (5-7years). Examining the feet of primary school aged children could help identify the effects of overweight and obesity on foot and arch development and the resulting implications.

Introduction

The prevalence of overweight and obesity has reached epidemic levels in many developed countries and obesity is considered to be one of the most serious health problems and common chronic illnesses of the 21st century (4, 31, 32). The past few decades have seen a worldwide increase in the number of children who are overweight or obese; childhood obesity and overweight is estimated to be around 20% of European populations, and around 14% in other developed countries (33, 34). Childhood obesity has been associated with long term health consequences and musculoskeletal issues, which include misalignment of the lower limbs, pain and discomfort (26, 31). Children and adolescents are growing rapidly and carrying excess mass can have a negative impact on the normal development of their bones, muscles and joints (35). Specifically, children are most susceptible to obesity-related musculoskeletal issues during growth phases, with the most intense phase occurring at pre-school age (26).

Feet are particularly affected by the additional mass a child with obesity must carry in everyday life. During walking and running, human feet have to tolerate loads that are at least 1-2 and 2-3 times greater than body mass, respectively (33). General foot structure can be affected by excess body weight at an early age of 3-5 years (32, 36). Overall foot dimensions of overweight children, including foot breadth and circumference are usually larger than those of normal weight children (31, 32). The most frequent condition seen in feet of overweight and obese children is flat feet, or pes planus (31, 33). It has been reported that children with obesity were 3.5 times more likely to suffer from pes planus feet compared to normal weight children (39). Although there is little research focused on the long term loading effects on the developing medial longitudinal arch of growing children, it is clear that the continual excessive pressure on the arch is related to the collapse of the arch and thus pes planus feet (39).

General configuration of the arch is partly determined by the age of a child (14). It is commonly agreed that changes in the arch are less apparent after the age of six years and should reach the same structure as that of an adult (15, 16). By the critical age of six years an adult like walking pattern can be found in most children, as the arch is believed to be fully developed. While excess mass has been shown to impact foot structure, no published studies have examined the relationship between obesity and foot development of primary school aged children at this critical stage. Yet, identifying risk factors during arch development in children is critical to diagnose any foot defects, as early treatment could prevent later symptoms in life (17, 18). Therefore, this study examined the impact of excess mass on the foot types and soft tissue structures of the foot in primary school aged children during the typical age of arch development (5-7years). It is hypothesised that children with excess mass will have larger intrinsic foot muscle morphology, but that the greater size will be insufficient in maintaining normal bony structure, resulting in lower and more flexible medial longitudinal arches. This hypothesis will provide mechanistic support for previous research, which indicates that excess body weight is highly correlated to pes planus foot type.

Methods

Participants

Eighteen female and twenty one male primary school aged children (mean age, 5.58± 0.67 years; mean height, 1.17m ± 0.07; mean weight, 24.13kg ± 6.53; mean BMI, 17.19 kg/m^2 ± 2.81) participated in this study. Participants were free of any neurological, metabolic and orthopaedic conditions that could affect gait. Participants were recruited from primary schools in the Wellington region of New Zealand. All recruiting and testing procedures were approved by the Massey University Human Ethics Committee: Southern A. Both parents and child gave written informed consent and assent, respectively, for participating.

Anthropometric measurements

Participant's body height was measured to the nearest tenth of a centimetre using a portable stadiometer (Seca 213, Hamburg, Germany). Participant's body mass was measured to the nearest 0.05kg using an electronic scale. Both height and mass were measured in barefoot condition. These data were then used to calculate each participant's body mass index (BMI; kg/m^2). Waist and hip circumference were measured using a non-elastic measuring tape with 0.1mm accuracy, in accordance with ISAK protocols (42). Body composition was measured using bioelectrical impedance analysis (Bodystat 1500MDD, Douglas, UK). Participants rested supine on a plinth for

10 minutes, while two electrodes each were placed on the right foot and right hand. One electrode was placed on the plantar aspect of the second toe, proximal to the metatarsal head. The second electrode was placed on the anterior aspect of the ipsilateral ankle between the medial and lateral malleoli. Within the upper extremity, one electrode was placed on the posterior aspect hand, just proximal to the third metacarpophalangeal joint; the second electrode was placed on the posterior aspect of the wrist, aligned with the articulation of the distal radioulnar joint. Body fat percentage was calculated using the equation derived for New Zealand children (43). Children were classified in normal weight, overweight, and obese groups according to previously determined cut-off points for body fat percentage, accounting for age and gender (44).

Foot structure

Foot type

To determine foot type, footprints were scanned and analysed using the Chippaux-Smirak index (CSI). Scanned images of the plantar aspect of the participant's feet were collected on a transparent 1cm thick plexiglass platform positioned directly above a flat-bed scanner (Brother DCP-J315W, Brothers Industries Ldt). Three footprint images were recorded in seated (non-weight bearing) and standing (weight bearing) position each, with feet shoulder width apart and weight evenly distributed in the standing position. CSI was determined as the minimum width of the midfoot arch region divided by the maximum width of the forefoot (16). The average values for all three measurements were used for analysis. CSI values of 0 to 0.09% indicate a pes cavus foot, between 0.1 to 45% pes rectus, and values over 45.1% indicate a pes planus foot (45). A foot type was considered flexible if the CSI classification changed between sitting and standing postures; otherwise, it was referred to as unchanged.

Soft tissue

A portable ultrasound system (Terason t3200, Burlington, MA) with a 38-mm broadband linear array transducer (22Hz, maximum depth 3cm) was used to measure the thickness and circumference of foot muscles as well as measuring the thickness of the plantar fat pad and plantar fascia. Participants lay prone with the feet at the end of the plinth in a neutral and relaxed position. To maintain consistency, all measurements were conducted on the participant's left foot. The ultrasound probe was placed along the line between the medial tubercle of the calcaneus and the third toe to assess flexor digitorum brevis (FDB) thickness. The ultrasound was positioned perpendicular to the aforementioned line to capture the cross-sectional area and muscle circumference of the FDB (46). The probe was longitudinally aligned with the first metatarsal when measuring the muscle thickness of the flexor hallucis brevis (FHB). To assess the cross-sectional area and circumference of the FHB, the probe was positioned perpendicular to the first metatarsal (46). The thickness of the plantar fascia (PF) was assessed in three different regions. The ultrasound probe was placed on the medial calcaneal tubercle and moved along the plantar aspect of the foot, distally towards the second toe. Ultrasound images were taken when the probe was positioned over the medial calcaneal tubercle (proximal), inferiorly aligned with the navicular tuberosity (middle), and just proximal to the head of the second metatarsal (distal) (46). The same image that was used for the middle portion of the PF was used to assess midfoot plantar fat pad (FP) thickness. To capture an image, the ultrasound system was paused and then the screen shot was saved. Images were saved when the borders of the soft tissue structures were clearly defined. Three trials and subsequent images were collected for each structure and the mean of the three trials was used for analysis. Structure thickness and circumference were measured using the Image J (ImageJ2) programme. The scale was set globally to 3cm and thickness was assessed with the straight line tool while circumferences were assessed with the freehand selection tool.

Reliability

Prior to data collection commencing, all ultrasound measurements were assessed for intra-rater reliability. Six adults, who were unrelated to the main study, were assessed by the same tester on two different days; each variable was assessed three times during each session. Intraclass correlation coefficient values ranged from R = 0.69 to 0.98 for all 8 of the measurements, with 6 values greater than 0.8 (Table 1). Based on standard correlation cut-off values, all measurements indicated high intra-rater reliability (47).

	R value
Plantar Fascia (prox)	0.91
Plantar Fascia (med)	0.74
Plantar Fascia (dis)	0.84
Fat pad	0.97
Flexor hallucis brevis (thickness)	0.91
Flexor hallucis brevis (cross-sectional)	0.69
Flexor digitorum brevis (thickness)	0.96
Flexor digitorum brevis (cross-sectional)	0.93

Table 1. Intraclass correlation coefficient values for soft tissues (prox=proximal, med=medial, dis=distal, t=thickness, x=cross-sectional area).

Statistical Analysis

Means and standard deviations (SD) were determined for all variables. Chi square analyses determined differences in the prevalence of foot type classification within each group. One-way analyses of variance (ANOVA) determined significant differences between groups for all soft tissue parameters. Stepwise multiple regression analyses predicted foot flexibility classification (unchanged=1; flexible=2) using soft tissue structures. Specifically, predictor variables included absolute values and values normalised to body mass for plantar fascia, fat pad, flexor hallucis brevis, and flexor digitorum brevis. All statistical tests were completed with SPSS 22 (IBM Corp, Armonk, NY). Significance was set at $P<0.05$.

Results

Participants

Participant data are displayed in table 2. According to body fat percentage for each participant, 25 participants were classified as normal weight, while 8 were classified as overweight and the remaining 6 as obese, with an overall mean body fat percentage of 17.5%.

	Normal Weight	Overweight	Obese
	Mean ± SD	**Mean ± SD**	**Mean ± SD**
Age (years)	5.48 ± 0.65	5.62 ± 0.74	6 ± 0.63
Height (m)	**1.15 ± 0.05^**	1.19 ± 0.06	**1.25 ± 0.06^**
Weight (kg)	**20.92 ± 2.9^**	26.05 ± 3.17	**34.95 ± 8.48^**
BMI (kg/m2)	**15.69 ± 1.11^***	**18.32 ± 0.87^{+}***	**21.93 ± 3.61^$^{+}$**
BF (%)	**15.51 ± 4.92^**	17.69 ± 5.88	**25.59 ± 4.87^**
LBM (kg)	**19.42 ± 4.23^**	19.48 ± 1.88	**23.15 ± 4.74^**

*Table 2. Participant description. (BMI= body mass index; BF = body fat; LBM = lean body mass; *significant differences between normal weight and overweight; ^significant differences between normal weight and obese; $^{+}$= significant differences between overweight and obese, p<0.05)*

Foot type

The majority of children presented with a pes rectus foot structure during sitting and standing (32 and 30 respectively). Pes cavus feet were more commonly seen during the non-weight bearing position, whereby 6 participants were classified with a flexible pes cavus foot type (7 during sitting and 1 during standing). The pes planus foot type was more commonly seen during weight bearing conditions, whereby 8 participants were classified with a flexible pes planus foot type (0 during sitting and 8 during standing) (Figure 1).

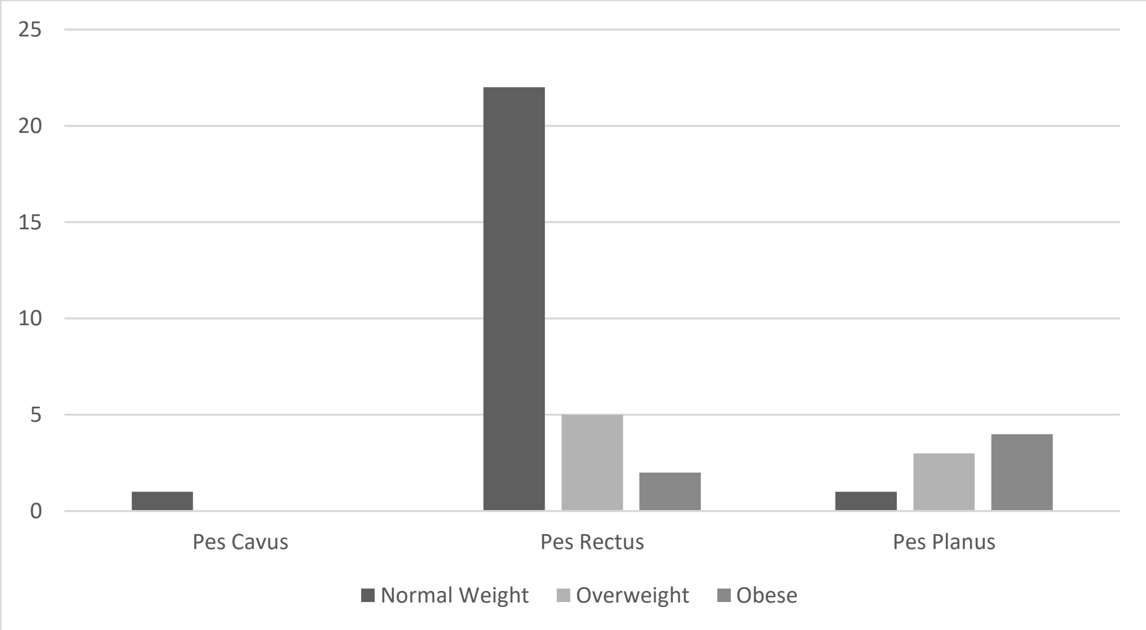

Figure 1. Foot type distribution across different weight classes during standing.

Statistical analysis revealed significant differences of foot types between normal weight, overweight, and obese children during sitting and standing (p=0.009 and p=0.006 respectively). Only one participant was classified with a pes cavus foot type. A total of 76.3% of participants were classified with a pes rectus foot type, with the majority being normal weight (57.9% in total). Only 21.1% of participants were classified with pes planus feet, with the majority being obese (10.5% in total).

		Flexibility Class	
		Unchanged foot type	**Flexible Foot Type**
Normal Weight	Count	18	6
Overweight	Count	5	3
Obese	Count	1	5

Table 3. Arch flexibility distribution within the different weight classes

Overweight and obese children showed significantly more flexible feet than normal weight children (p=0.03) (Table 3). Within the normal weight group 75% of children displayed an unchanged foot type, within the overweight group 62.5% of children displayed an unchanged foot type, and within the obese group 63.2% displayed an unchanging foot type.

Soft tissue

Significant differences in soft tissue morphology were only found between the different weight classes when parameters were normalised to lean body mass or body mass (Table 4). Obese children displayed significantly smaller plantar fat pads compared to normal weight children when normalised to body mass (p=0.04). Obese children also displayed a significantly smaller proximal plantar fascia compared to normal weight children when normalised to lean body mass and body mass (p<0.001 and p=0.04 respectively). Both overweight and obese children showed a significantly smaller middle plantar fascia thickness compared to normal weight children when normalised to lean body mass (p=0.019, p=0.02 respectively) and body mass (p=0.007 and p<0.001 respectively). Overweight children had a significantly smaller distal plantar fascia compared to normal weight children when normalised to lean body mass (p=0.035). Furthermore, obese children had a significantly smaller distal plantar fascia compared to normal weight children when normalised to lean body mass and body mass (p=0.013 and p=0.001 respectively).

		Normal weight	Overweight	Obese	Total
		Mean ± SD	**Mean ± SD**	**Mean ± SD**	**Mean ± SD**
Fat Pad (mm)	ABS	0.45 ± 0.115	0.496 ± 0.118	0.538 ± 0.041	0.473 ± 0.111
	LBM	0.028 ± 0.007	0.026 ± 0.003	0.024 ± 0.003	0.027 ± 0.006
	BM	**0.022 ± 0.006^**	0.02 ± 0.002	**0.016 ± 0.003^**	0.02 ± 0.005
Plantar Fascia proximal (mm)	ABS	0.17 ± 0.016	0.179 ± 0.03	0.17 ± 0.028	0.172 ± 0.021
	LBM	**0.011 ± 0.002^**	0.009 ± 0.002	**0.008 ± 0.002^**	0.01 ± 0.002
	BM	**0.008 ± 0.001^**	0.007 ± 0.001	**0.005 ± 0.001^**	0.008 ± 0.002
Plantar Fascia medial (mm)	ABS	0.137 ± 0.16	0.135 ± 0.013	0.14 ± 0.014	0.137 ± 0.014
	LBM	**0.009 ± 0.002^***	**0.007 ± 0.001***	**0.006 ± 0.001^**	0.008 ± 0.002
	BM	**0.007 ± 0.001^***	**0.005 ± 0.001***	**0.004 ± 0.001^**	0.006 ± 0.001
Plantar Fascia distal (mm)	ABS	0.112 ± 0.017	0.114 ± 0.012	0.125 ± 0.018	0.114 ± 0.017
	LBM	**0.007 ± 0.001^***	**0.006 ± 0.001***	**0.006 ± 0.001^**	0.007 ± 0.001
	BM	**0.005 ± 0.001^**	0.004 ± 0.001	**0.004 ± 0.001^**	0.005 ± 0.001

*Table 4. Group differences of weight classes and soft tissue sizes (ABS=absolute, LBM=normalised to lean body mass, BM=normalised to body mass; *significant differences between normal weight and overweight; ^significant differences between normal weight and obese, += significant differences between overweight and obese, p<0.05).*

The thickness of the flexor hallucis brevis was the only muscle tissue to show significant size differences between weight classes in terms of absolute size and when normalised to lean body mass and body mass (Table 5). FHB thickness was significantly larger for overweight (p=0.029) and obese children (p=0.05) compared to normal weight children in absolute terms. Obese children also had a significantly smaller FHB thickness compared to normal weight children when normalised to lean body mass and when normalised to body mass (p=0.08, and p=0.00 respectively). Obese children had a significantly smaller cross-sectional area of FHB compared to normal weight children when normalised to lean body mass (p=0.001) and body mass (p=0.007). Furthermore, obese children also had a smaller FHB thickness (p=0.017) and smaller FDB cross-sectional area (p=0.001) compared to normal weight children when normalised to body mass.

		Normal weight	Overweight	Obese	Total
		Mean ± SD	**Mean ± SD**	**Mean ± SD**	**Mean ± SD**
Flexor Hallucis Brevis					
Thickness (mm)	ABS	**0.936 ± 0.089^***	**1.029* ± 0.087***	**1.032 ± 0.046^**	0.969 ± 0.094
	LBM	**0.06 ± 0.009^**	0.053 ± 0.008	**0.046 ± 0.009^**	0.056 ± 0.01
	BM	**0.045 ± 0.007^**	0.04 ± 0.007	**0.031 ± 0.006^**	0.042 ± 0.009
Cross-Sectional area (mm^2)	ABS	2.354 ± 0.273	2.625 ± 0.306	2.54 ± 0.236	2.438 ± 0.292
	LBM	**0.149 ± 0.02^**	0.137 ± 0.02	**0.112 ± 0.018^**	0.141 ± 0.024
	BM	**0.114 ± 0.015^**	**0.104 ± 0.02$^+$**	**0.075 ± 0.013^$^+$**	0.106 ± 0.021
Flexor Digitorum Brevis					
Thickness (mm)	ABS	0.637 ± 0.203	0.615 ± 0.037	0.672 ± 0.139	0.638 ± 0.638
	LBM	0.04 ± 0.011	0.032 ± 0.004	0.03 ± 0.009	0.037 ± 0.011
	BM	**0.03 ± 0.009^**	0.024 ± 0.003	**0.02 ± 0.006^**	0.028 ± 0.009
Cross-Sectional area (mm^2)	ABS	0.955 ± 0.165	1.1065 ± 0.133	1.122 ± 0.196	1.003 ± 0.173
	LBM	0.061 ± 0.012	0.055 ± 0.006	0.049 ± 0.005	0.058 ± 0.011
	BM	**0.046 ± 0.009^**	0.041 ± 0.003	**0.033 ± 0.005^**	0.043 ± 0.009

*Table 5. Group differences of weight classes and muscle sizes (FHBt= flexor hallucis brevis thickness, FHBx= flexor hallucis brevis cross-sectional area, FDBt= flexor digitorum brevis thickness, FDBx= flexor digitorum brevis cross-sectional area ABS=absolute, LBM=normalised to lean body mass, BM=normalised to body mass; *=significant difference between normal weight and overweight, ^=significant differences between normal weight and obese, $^+$= significant differences between overweight and obese, $p<0.05$).*

The stepwise regression analysis identified 4 soft tissue parameters through four steps to predict arch flexibility (Table 5). The proximal plantar fascia thickness, thickness and cross-sectional area of flexor hallucis brevis, and flexor digitorum brevis thickness when normalised to body mass have the greatest influence on arch flexibility, correctly predicting 84% of the feet as being flexible or unchanged.

	Regression Equation	**Percentage of correct classification**	**R^2**
Step1	11.408-69.891(PFprox)	75.7	0.379
Step2	21.238-93.306(PFprox)-138.949(FDBxM)	81.1	0.538
Step3	14.665-118.604(Pfprox)+11.341(FHBt)-140.173(FDBxM)	83.8	0.624
Step4	25.27-141.28(PFprox)+22.04(FHBt)-5.3(FHBx)-248.8(FDBxM)	83.8	0.715

Table 6. Table 5: Regression equation for predicting the influence of soft tissue structures on arch flexibility (PFprox=proximal plantar fascia, FHBt=flexor hallucis brevis thickness, FHBx=flexor hallucis brevis cross-sectional area, FHBxM=flexor hallucis brevis cross-sectional area normalised to body mass).

Discussion

Although previous research has investigated plantar fat pad in obese children (37), this is the first study to examine the impact of excess mass on a variety of soft tissue structures of primary school aged children during the critical stage of arch development. The obese children had larger absolute intrinsic foot morphology, but smaller morphology when the parameters were normalised to body mass or lean body mass. Thus, the first half of the hypothesis was partially accepted. The foot type of obese and overweight children was more frequently classified as flexible; thus, the second half of the hypothesis was accepted.

Soft tissues structures that were examined via ultrasound included the proximal, medial and distal plantar fascia, the plantar fat pad and the thickness and cross-sectional area of both the FDB and FHB. Significant difference between the normal weight, overweight and obese group of soft tissue structures were found when measurements were normalised to lean body mass and body mass. Overweight and obese children have smaller soft tissue structures compared to normal weight children relative to their body mass. These results indicate that the intrinsic musculature of overweight and obese children may not be capable of carrying the extra load, thus causing the medial longitudinal arch to collapse. Therefore, the results of our study further support the hypothesis that although the absolute morphology of obese children might be larger than normal weight, the capacity to function under excessive load may be diminished. These functional limitations in foot musculature align with similar impairments presented in knee extensor (48) and hip abductor (49) muscles of obese children.

The majority of obese children in this study had a flexible foot type, indicating that as body mass increases, arch flexibility increases. These results agree with previous research, whereby overweight and obese children have a high prevalence of flexible feet (50, 51). Studies have suggested that the excess weight can cause changes in the plantar arch by influencing the support of the osseous and ligamentous support, thus causing the arch to collapse (32). However, the mechanistic theory has not been fully supported by research. The results of the regression analysis showed that the thickness and cross-sectional area of the flexor hallucis brevis, the proximal plantar fascia, and flexor digitorum brevis thickness when normalised to body mass seemed to have the strongest influence on arch flexibility. A smaller proximal plantar fascia, smaller FHB cross-sectional area, and smaller FDB cross-sectional area when normalised to body mass, show a higher arch flexibility. As these soft tissue structures become smaller they are unable to carry the extra load carried with obese children, thus causing the flexible foot to collapse. Interestingly, the FHB thickness seemed to also greatly influence arch flexibility, indicating a higher arch flexibility with greater FHB thickness. Unfortunately, we are unable to explain this anomaly, and further research is needed to examine the FHB tissue in relation to arch flexibility and development.

Obese children not only showed more flexible feet but also flatter feet. Overweight and obese children represented a higher number of a pes planus foot type when standing. These results are in line with previous studies reporting lower foot print angles and higher Chippaux Smirak index in overweight and obese children (31, 32). Some researchers have argued that using the footprint analysis will provide inaccurate results due to the variability of plantar fat pad thickness in children (51). However, similar to Mickle et al. (37), our study reported no significant differences of fat pad thickness in different weight groups, further supporting the notion that overweight and obese children do have flatter feet, which are influenced by changes in foot structures rather than increased fat pad thickness. A decreased arch height and increased arch flexibility have been considered significant predictors of knee symptoms and hip/back symptoms in children (52). According to Kothari et al. (52) a small reduction of just 0.01 in the arch height index increases the chances of having knee symptoms by nearly 30%. Thus, our results combined with results from previous studies highlight the importance of early intervention and strengthening training in overweight and obese children foot muscles to reduce the incidence of symptomatic flat feet later in life.

Limitations

This study did have some limitations. All measurements were only performed on the left foot. Future research could include measurements of both feet or the dominant foot of each participant. Although this study is the first to examine the foot of primary school aged children, the sample size was limited, which was reflected in the small cohort for non-rectus foot types. Future research examining the feet of primary school aged children should further examine the role of the flexor hallucis brevis muscle in arch development and include more soft tissue as well as bony structures.

Conclusion

To conclude, this research examined the feet of primary school aged children (5-7 years) in terms of foot types and soft tissue structures. Specifically, this study examined how body mass can affect the arch in young children during the critical stage of arch development. Results showed that there was a higher correspondence of pes planus feet in the overweight and obese groups. Furthermore, there was a higher correspondence of flexible feet in the overweight and obese groups compared to the normal weight group. As body fat percentage increases, the size of soft tissue structures that play vital roles in supporting the medial longitudinal arch, decreased when normalised to body mass. These soft tissue structures are therefore not capable of carrying the extra load in overweight and obese children, causing the collapse of the arch. Early strengthening programmes of the muscles supporting the medial longitudinal arch could help prevent the collapse of the medial longitudinal arch and the accompanying symptoms.

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