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Advances in the application of orthotic insoles for flatfoot treatment

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Abstract

Structural abnormalities in the foot arch, such as flatfoot, can cause issues like plantar fasciitis and hallux valgus. Orthotic insoles effectively alleviate discomfort by enhancing plantar proprioception, optimizing pressure distribution, and improving ankle stability. Custom insoles, particularly for children, restore the arch and compensate for its function, showing significant benefits for patients with severe symptoms or multiple joint disorders. However, challenges include unclear biomechanical mechanisms, limited long-term follow-up data, and insufficient studies under weight-bearing conditions. Future research should involve rigorously designed, large-scale clinical trials to explore the long-term efficacy of custom insoles and their biomechanical effects in diverse flatfoot populations.

Keywords: flatfoot, orthotic insoles, biomechanics, healthcare

1. Introduction

Flatfoot is a common foot abnormality characterized by arch collapse, forefoot abduction, and hindfoot eversion. In diagnosis, weight-bearing X-ray imaging is considered a precise method. A Meary's angle greater than 4° on a lateral radiograph is indicative of flatfoot; 15°< Meary's ≤ 30°indicates moderate flatfoot, and >30° indicates severe flatfoot [1]. Footprint analysis and morphological measurements are often used for large-scale epidemiological studies and initial clinical screening due to their simplicity, low cost, and non-invasiveness, but they involve a certain degree of subjectivity. Studies have shown that the prevalence of flatfoot in preschool children can reach up to 45%, while in adults, the prevalence is about 5%-15% [2]. Flatfoot can lead to fatigue and pain in the feet after prolonged standing or walking and may cause discomfort in other areas through kinetic chain reactions and compensatory mechanisms, such as medial tibial stress syndrome, knee pain, pelvic tilt, lumbar lordosis, and back pain [3]. This can reduce the quality of life for the patient, physical activity, and even their social participation.

Orthotic insoles are a common treatment for flatfoot, providing arch support and redistributing plantar pressure to restore normal biomechanical structure, thereby alleviating symptoms and preventing disease progression [4]. Clinically, orthotic insoles are mainly categorized into three types: prefabricated, semi-custom, and custom-made. Their use can help some patients avoid surgical treatment and significantly improve their quality of life. This article will summarize recent research, focusing on the design of orthotic insoles and their impact on the biomechanics of the lower limbs in flatfoot patients, aiming to provide a reference for future research and technological development.

2. Materials and methods

2.1 Sources of information

This study collected relevant literature published from September 2014 to September 2024 by searching the full-text databases of PubMed, Web of Science, and Embase. The English keywords used for the search included "flatfeet," "orthopedic insoles," "foot orthoses," "effect," "biomechanics," and "mechanism." The types of literature included were research articles, reviews, case reports, meta-analyses, and guidelines.

2.2 Inclusion and exclusion criteria

The inclusion criteria for this study involved an initial screening based on the article title and abstract, followed by a thorough reading to identify research articles, reviews, case reports, meta-analyses, and guidelines closely related to the design and application of orthotic insoles in the treatment of flatfoot. Additionally, important references from high-quality literature were included.

The exclusion criteria were: excluding literature that had a weak correlation with the research objective or target population, as well as studies with a high degree of redundancy.

3. Results

3.1 Flatfoot

The foot arch is formed by the tarsal bones, metatarsal bones, and foot joints, ligaments, and tendons, creating an upward convex arch structure that can be divided into the longitudinal and transverse arches. The medial longitudinal arch, known as the elastic arch, is responsible for the elastic function of the foot arch, while the lateral longitudinal arch, called the supporting arch, mainly maintains the upright posture of the body. According to the distribution of plantar pressure, the front ends of the two longitudinal arches bear about 40% of the plantar pressure, and the rear ends bear about 30%; the lateral transverse arch accounts for 15%, the big toe accounts for 15%, and the remaining four toes account for 7%. The total pressure on the forefoot and toes accounts for 52%. The foot arch functions like an arch bridge, capable of bearing weight and reducing compression on the nerves and blood vessels of the foot.

Flatfoot is typically defined as a lowering or disappearance of the medial arch, accompanied by hindfoot valgus and talar descent (Figure. 1). The causes of flatfoot can be congenital or acquired. Congenital factors include genetics and foot deformities, manifesting as congenital arch collapse, ankle joint instability, and abnormal gait. Acquired flatfoot is related to factors such as obesity, injury, foot soft tissue underdevelopment, prolonged standing, and excessive foot load, which can lead to fatigue of the structures that maintain the arch or foot fractures. Studies have shown that flatfoot patients experience increased peak plantar pressure, leading to foot injury [5]. Additionally, flatfoot patients have a higher arch index and ankle inversion index compared to those with normal feet. Research analyzing the muscle groups around the ankle joint during exercise in flatfoot patients found that due to weaker ankle dorsiflexor strength, patients compensate by increasing the flexion angles of the hip and knee joints [6]. Furthermore, a low arch causes a higher recruitment of deep muscles in the posterior lower leg during the support phase. This suggests that flatfoot patients have an uneven distribution of plantar pressure, which can compress the blood vessels and nerves in the foot and lead to compensatory abnormalities in the lower limb muscles, affecting foot stability.

Flatfoot patients often experience plantar pain, foot deformities, knee pain, and abnormal gait due to abnormal arch structure and biomechanical dysfunction, potentially leading to secondary conditions such as plantar fasciitis and scoliosis. Research has found that flatfoot patients have a longer proportion of time in the heel-strike phase and a shorter duration in the heel-off phase during the gait cycle, indicating poor cushioning and push-off capabilities during walking [7]. The imbalance in plantar pressure significantly increases the load on the metatarsals, accelerating the process of arch damage. In terms of lower limb muscle activity [8], studies have found that flatfoot patients show significantly increased activity in the tibialis anterior and rectus femoris muscles when climbing stairs, along with increased electromyographic activity in the tibialis anterior, gastrocnemius (both medial and lateral heads), and rectus femoris muscles [9]. These changes reflect compensatory responses in the feet of flatfoot patients during stair climbing to prevent excessive external rotation. Therefore, the abnormal distribution of plantar pressure in flatfoot patients often leads to muscle tissue damage and is accompanied by compensatory foot movement abnormalities.

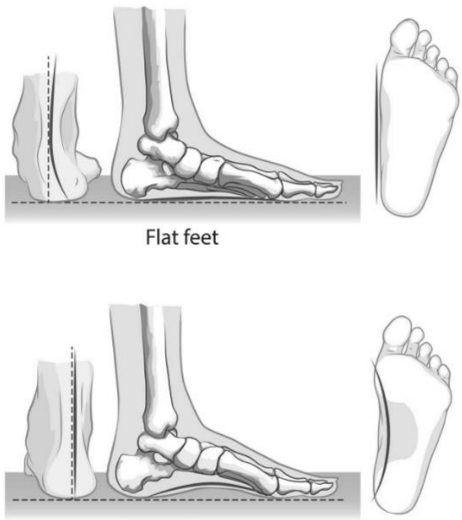

Figure 1. Differences between flatfoot and normal foot

3.2 Design principles of orthotic insoles for flatfoot treatment

In a normal gait cycle, during the early support phase (from heel strike to loading response), muscles such as the tibialis posterior and gastrocnemius contract, allowing the subtalar joint to pronate and the intertarsal joints to relax, helping the foot adapt to different terrains. When the heel leaves the ground, the subtalar joint supinates, locking the intertarsal joints. The plantar fascia then tightens the alignment of the foot bones, transforming into a rigid lever to propel the body forward. However, due to abnormal arch morphology in flatfoot patients, the segmented multi-joint movements of the foot are disturbed, and local stress increases, leading to forefoot pronation and abduction, and hindfoot valgus. Studies using in vivo experiments to simulate foot and ankle movements during walking have confirmed that flatfoot patients exhibit more pronounced eversion and external rotation of the calcaneus compared to those with normal feet [10]. This phenomenon increases ankle instability and affects the biomechanical axis of the lower limbs and trunk through the kinetic chain. Abnormal joint movements can also cause local tissue edema, inflammation, and pain, eventually leading to postural abnormalities. Prolonged irregular force patterns may cause cartilage damage and even irreversible consequences.

Orthotic insoles correct abnormal gait by adjusting plantar pressure distribution based on biomechanical analysis (Figure 2). The foot, as a support point for the body, bears weight and participates in activities such as walking and running. However, due to differences in gender, lifestyle habits, and exercise methods, the mechanical distribution of the foot can be affected. Prolonged uneven pressure may lead to abnormalities in lower limb force lines, causing various diseases. In daily life, various pathological factors can disrupt the normal state of lower limb force lines. Orthotic insoles can readjust plantar pressure and restore normal lower limb force lines, thereby improving the biomechanical state of the lower limb joints [11]. Due to individual differences in walking habits, foot morphology, and pathology, there are individual variations in plantar pressure distribution. Orthotic insole correction can help distribute plantar pressure more evenly, enhance foot dynamics, and subsequently restore normal lower limb force lines.

Figure 2. Common designs of orthotic insoles

Material Selection: Common materials for making orthotic insoles include thermoplastic polyurethane, ethylene-vinyl acetate, and polyethylene. While some studies suggest that harder insole materials can increase plantar sensory input, thus enhancing postural stability, the hardness of custom orthotic insoles mainly affects their shock absorption, arch support, and comfort [12]. Materials of different hardness can impact the cushioning effect of plantar pressure during standing and walking. Some researchers have found that patients with higher body mass index require harder materials to achieve optimal cushioning [13]. Moreover, research indicates that harder materials have a more significant effect on arch support, but increased hardness may decrease patient comfort [14]. Therefore, it is necessary to select appropriate materials based on the patient's specific condition to achieve a balance between support strength, shock absorption, and comfort.

Shape Design: Compared to material selection, the geometric shape design of orthotic insoles has a greater impact on their function. For flatfoot structural abnormalities, the insole design mainly includes the following two aspects:

Medial Arch Support Design: By adding an arch pad with an arched structure, the insole can support the arch upward, increasing the contact area between the medial arch and the insole, reducing the peak pressure on the forefoot and heel, and thereby dispersing local stress. Additionally, the arch pad can elevate the navicular, medial cuneiform, and calcaneus, helping to maintain the normal arch shape and improve the mobility of the foot and ankle joints. Studies have shown that the higher the arch pad, the more pronounced the elevation of the navicular, with a more significant effect on improving plantar pressure distribution and higher comfort [15].

Deep Heel Cup Design: A downward concave deep heel cup can restrict excessive pronation of the subtalar joint, reduce displacement of the hindfoot soft tissue, and provide good cushioning and shock absorption by increasing the thickness of the heel fat pad, effectively reducing heel peak pressure. A study designed nylon heel cup insoles with a thickness of 5 mm for 16 patients, and after four weeks of use, the patients experienced significant relief from heel pain [16]. Custom orthotic insoles often combine arch support and heel cup design. Research indicates that elderly subjects who consistently wear such insoles for more than four hours daily for eight weeks show significant improvement in standing balance, while decreased postural stability is also a common problem in some flatfoot patients [17].

3.3 Orthotic insoles for patients of different ages

In recent years, the incidence of flatfoot in children and adolescents has gained widespread attention. A study of 2 071 children aged 3-5 found a flatfoot incidence rate of 59.98%, with a higher occurrence of bilateral flatfoot than unilateral flatfoot [18]. Another study assessing 444 children aged 7-13 found a prevalence of 29.10%, indicating that the occurrence of flatfoot is closely related to factors such as age, gender, and BMI [19]. Early intervention and treatment are particularly important for school-age children. A three-year follow-up study of 147 children aged 7-8 found that the arch index of flatfoot children showed an increasing trend over time, with plantar pressure increasing in the first and second years, peaking before declining [20]. This indicates that arch abnormalities can lead to uneven distribution of plantar pressure. Another study found that in children with flatfoot, the contact area of the fourth metatarsal is smaller during standing, while the contact area of the first metatarsal is smaller during movement, further demonstrating the importance of orthotic insoles in flatfoot intervention [21].

Research shows that orthotic insoles have a significant corrective effect on flexible flatfoot [22]. One study pointed out that early childhood flexible flatfoot is a normal physiological state, but if it is not corrected with development, it may develop into pathological flatfoot [23]. Therefore, early intervention is crucial. Another study found that when the arch support height reached 4/5 of the normal arch height, orthotic insoles had the best intervention effect on pediatric flexible flatfoot, while increasing ankle inversion angle and reducing internal rotation torque [24].

However, research on orthotic insoles for children and adolescents still has some shortcomings [25]. There is a lack of unified evaluation standards and long-term follow-up data, and little attention is paid to the long-term wearing experience and the damage to orthotic insoles. Additionally, there is a scarcity of studies on the biomechanical feedback of the plantar during movement in patients. Therefore, future research should develop appropriate evaluation scales for children, increase long-term follow-up, and further explore plantar biomechanical data during movement.

For adult flatfoot, orthotic insoles cannot completely correct the arch but can improve plantar pressure distribution, correct abnormal biomechanics, and alleviate symptoms to some extent. Research indicates that adult flatfoot patients exhibit abnormal gait, with a shortened single-leg support phase and an extended double-leg support phase, suggesting that patients increase lateral support to maintain gait stability. These findings provide theoretical support for the customization of orthotic insoles [26].

Through orthotic insole intervention, patients' plantar pressure is significantly improved. One study found that orthotic insoles can reduce the peak ground reaction force during the gait support phase and change the recruitment pattern of lower limb muscles [27]. Another study examined the impact of orthotic insoles on the lower limb electromyographic activity in female flatfoot patients and found that the peroneus longus and medial and lateral heads of the gastrocnemius muscles showed higher electromyographic levels, leading to easier fatigue [28]. After orthotic insole intervention, the electromyographic activity of these muscles was significantly reduced, thereby alleviating the fatigue caused by compensation.

However, there are also some issues with the use of orthotic insoles. One study showed that although orthotic insoles can enhance hindfoot support stability, they may also lead to compensatory activity in the hip and knee joints, thereby limiting foot push-off ability and affecting lower limb flexibility [29]. Therefore, how to reasonably use orthotic insoles to improve flatfoot symptoms while avoiding compensatory issues becomes a key challenge in the treatment of adult flatfoot patients.

4. Summary and prospects

The foot is a highly plastic structure, and orthotic insoles can effectively correct flatfoot by adjusting plantar pressure distribution and restoring lower limb alignment. In clinical studies, early detection and intervention for flatfoot in children and adolescents are emphasized to prevent worsening of the condition. For adult flatfoot patients, while orthotic insoles have some corrective effects, they cannot fully restore arch function. Orthotic insoles not only enhance patients' plantar proprioception and improve their subjective feedback to pressure changes but also effectively redistribute plantar pressure, alleviate abnormal gait, and increase ankle joint stability. In addition, orthotic insoles can provide relief from abnormalities or pain in the lower back, knees, and ankles caused by flatfoot. With long-term use of orthotic insoles, patients experience enhanced plantar flexion strength in the ankle, improved overall lower limb muscle strength, recovery of compensatory muscles, better support of the lateral arch, and effective correction of ankle eversion.

Current research has certain limitations: the mechanism behind orthotic insoles in treating flatfoot involves selecting appropriate materials and shapes to restore arch morphology and compensate for arch function, but the specific biomechanical mechanisms remain to be explored. There is a lack of long-term follow-up data from patients, resulting in insufficient feedback. Additionally, biomechanical analysis studies on patients wearing orthotic insoles during physical activity or under load-bearing conditions are relatively scarce. Children with flatfoot benefit more from custom orthotic insoles than adults, and patients with significant clinical symptoms or multiple foot, ankle, or knee disorders should prioritize the use of orthotic insoles. Future studies should focus on rigorous designs and large sample sizes to evaluate the efficacy of custom orthotic insoles in different flatfoot populations.

7. References

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