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How Foot Weight-Bearing is Associated with Posture, Balance, And Gait: A Narrative Review

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Abstract: *The flexible and rigid anatomy of the human foot contributes to both static and dynamic motion of the body. Foot muscles are crucial to maintaining foot-ankle posture and static balance. Intrinsic muscle activity fires more frequently to maintain balance and static posture. The principal foot mobilizers, extrinsic foot muscles, oversee ankle motion and balance control. A paucity of evidence outlines a distinct relationship between foot posture and balance, ultimately leading to gait abnormalities. Thus, this review examines the relationship between musculoskeletal disorders and foot posture, balance, and gait. It postulates that foot changes caused by any disorder may or may not affect their balance and gait. Somatosensory changes become impaired when the foot is pronated, affecting joint mobility or the surface contact area needed to maintain a stable support base. During joint motion, proprioceptive feedback depends on sensory information from the plantar sole mechanoreceptor, visual, vestibular, and proprioceptive senses. The shift in heel position impairs balance due to changes in sensory receptor participation, muscle stretch, and inactive components surrounding the ankle joint. The effects of functional postures and occupational demands are reviewed in firefighters and musicians. This review highlights the association between foot posture, balance, and gait.*

Keywords: *Foot weight-bearing, posture, foot posture and balance, gait, firefighter's fee*

1. Introduction

The flexible and rigid anatomy of the human foot contributes to both static and dynamic motion of the body. The foot aids in maintaining equilibrium in any external environment, provides body weight support, and functions as a shock absorber. The supporting structures of the foot are the transverse, lateral longitudinal, and medial longitudinal arch (McKeon et al., 2014; Welte et al., 2018; Panichawit et al, 2015; Lee & Choi, 2016). Foot muscles are crucial to maintaining foot ankle posture, and static balance. Intrinsic muscle activity fires more frequently to maintain balance and static posture in foot disorders (Ferrari et al., 2020). The principal foot mobilizers, which are extrinsic foot muscles, oversee ankle motion and balance control, while the foot stabilizers, intrinsic foot muscles (Fig.1), help stiffen the longitudinal arch or forefoot (McKeon et al., 2014; Ferrari et al., 2020; Kelly et al., 2012).

The flexor digitorum longus and flexor hallucis longus are the primary foot mobilizers. The secondary foot mobilizers include tibialis posterior and calf muscles. The foot muscles shape, support, and build the foot arch and support additional mechanical stress during extreme static and dynamic postural challenges. Muscle and articular chain changes cause modification of proximal joints leading to aberrant posture. When this muscle activity does not provide the required support, compensatory muscles begin to contract, weakening the muscles in the feet. Medial longitudinal support is lessened by increased extrinsic muscular strength, which results in flat feet, especially in the older population (Endo et al., 2002; Gheitasi et al., 2022). Somatosensory changes become impaired when the foot is pronated, affecting joint mobility or the surface contact area needed to maintain a stable support base. In the case of foot pronation, peripheral input is altered, requiring proximal postural adjustments to maintain upright posture and balance (Figure 1).

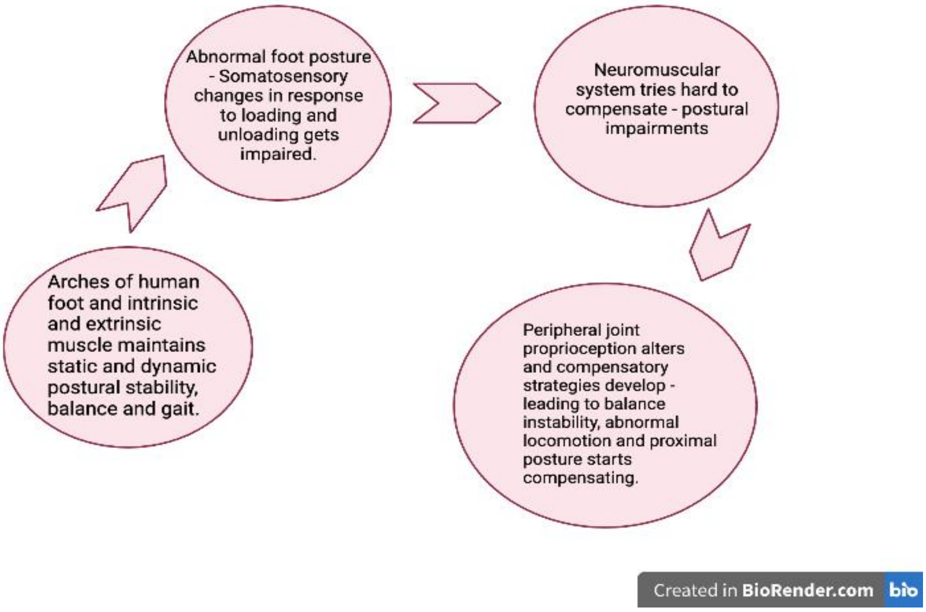

Figure 1: Relationship between foot, posture, and gait.

Displacement during lower extremity movements in oblique and lateral directions decreases with a flat foot. Overpronation of the foot tends to collapse toward the medial aspect of the foot, making it harder to maintain rigid support when bearing weight. Medial deviation, greater foot mobility, and decreased dynamic reach in the lateral direction are all characteristics of pronators. To maintain dynamic balance, overpronation necessitates enhanced proprioception in the lower extremity joints, neuromuscular control, and muscle strength coordination (Reimann & Lephart, 2002).

During joint motion, proprioceptive feedback depends on sensory information from the plantar sole mechanoreceptors, visual, vestibular, and other proprioceptive senses. Foot structural abnormalities can cause the heel valgus, or rear foot angle, to rise. The shift in heel position impairs balance due to changes in sensory receptor participation and muscle stretch reflex, causing prolonged-latency efferent responses (Paulus et al., 1984; Cathers et al., 2005; Horak et al., 1995; van Deursen & Simoneau, 1999; Menz et al., 2006).

Ankle complex proprioception signals information regarding joint position and movement sense, the velocity of muscular contractions, and the force/effort in response to the ankle's muscle contractions. The optimal function of the ankle complex depends on the synergy between the muscles, connective tissue, joints, and motor and sensory signaling, resulting in the maintenance of balance and postural stability (van Deursen & Simoneau, 1999).

The dynamometric map hypothesis explains the association between plantar sole sensitivity in the foot and standing balance control. According to the hypothesis, the foot and ankle work synergistically to facilitate postural adjustments in response to changes in the foot center of pressure. The loss of plantar cutaneous sensitivity causes partial ischemic pressure at the foot in older adults, resulting in postural instability (Menz et al., 2006; Kavounoudias et al., 2001; Wrestlake et al., 2007). Plantar cutaneous sensation and proprioception both change with age due to decreased tactile mechanoreceptors. Thus, fallers have a higher tactile sensory threshold at the metatarsophalangeal joint than non-fallers (Menz et al., 2006).

In the loaded position on the ground, mechanoreceptor activity is primarily distributed in the foot, whereas in the unloaded position, no activity is observed (Benjuya et al., 2004; Chen & Qu, 2019; Menz et al., 2004; Sturneiks et al., 2004; Ivanenko & Gurfinkel 2018). It has been demonstrated that engaging in physical activity increases the stimulation of plantar sole cutaneous mechanoreceptors. Stance walking (normal walking with the weight of the entire body on foot) becomes challenging when abnormal foot proprioception interferes with body posture and postural oscillations (Han et al., 2015; Billot et al., 2013; Wang & Lin, 2008). Therefore, correct foot posture is essential to the human body's functional locomotion. Additionally, in closed kinematic chain activities, the foot's position can also alter the position of the spine, pelvis, and lower extremities. When an individual has pronated (flatfoot), the medial arch diminishes, causing adduction and medial rotation of the talus, eversion of the calcaneus, and adduction of the forefoot. This change in foot posture causes internal rotation of the tibia, causing more stress on the quadriceps and increasing the Q angle. These alterations in lower extremity postures cause stress on the spine, increasing the probability of lumbar lordosis and thoracic kyphosis. These postural changes cause an increase in the prevalence of musculoskeletal injuries and conditions (Ingle & Puntambekar et al., 2020).

Evidence has made it clear that functional limitations in the proximal body result from incorrect foot posture. Reviewing the literature on the relationship between plantar sole mechanoreception, balance and gait control, ankle function, and foot architecture is crucial to understanding these factors' intricate interplay. By examining existing research, we aim to identify the intricate mechanisms underlying foot biomechanics, elucidate the impact of plantar sole sensory feedback on balance and gait, and potentially uncover valuable insights for clinical applications such as designing interventions for improving ankle function and foot-related pathologies.

1.1. Ankle Complex Proprioception And Plantar Cutaneous Sensation In Older Women

In Kavounoudias et al. (1998) seminal work, "The plantar sole is a 'dynamometric map' for human balance control" there was a strong correlation between ankle complex proprioception and plantar cutaneous sensation. According to the theory, the plantar sole is an important source of information for making the small adjustments necessary to keep the foot in balance. Textured insoles have been utilized effectively as an immediate treatment to enhance plantar sole stimulation and have enhanced ankle complex proprioception and balance performance. Plantar skin sensitivity was higher in older adults with a high or moderate level of long-term physical activity than in the inactive older group because it stimulates more cutaneous mechanoreceptors.

Kennedy and Inglis (2002) reported 104 cutaneous mechanoreceptors situated in the sole of the foot, among which 31 were slow adapting, and 75 were fast adapting cutaneous mechanoreceptors. Sole is found to have a high dynamic sensitivity since they distinguish more quick adjusting units than slow adjusting units there.

1.2. Pes Planus and Balance in Athletes and Obese Individuals

The neutral arch, the pes planus (flat sole), and the pes cavus (high arch) are the most common foot arch types. The physiological biomechanics of the foot is affected by any issue with the calcaneal tubercle, the first metatarsal head, or the arches. The general term "pes planus" refers to the complete or partial flattening of the medial longitudinal arch during loading. Pes planus causes pronation and plantar flexion in the foot and adduction of the talus and valgus of the calcaneus during weight bearing. The abnormal sensory input from the foot caused by this deviation from normal foot alignment hinders the proper muscle activity required for body posture and postural oscillations. Because of this, the intrinsic and extrinsic muscles are under more stress and must work harder to compensate for the lack of foot balance. Pes planus is the most common form of abnormal foot posture, affecting balance and making walking or running difficult. It has been discovered that athletes with pes planus have a poor foot control in the ankle and foot complex, resulting in poor balance and jump performance. Thus, we believe that early evaluation is necessary for the presence of pes planus to minimize postural abnormalities leading to musculoskeletal dysfunctions. Sports performance needs to identify athletes with pes planus and implement the necessary corrective exercise strategies (Sahin et al., 2022; Jacob, 2001; Keller, et al., 1996).

Pes Planus is common among preschool-aged children but less prevalent in adults, with most cases being the flexible form where the arch appears normal except when standing. In children, exposure to physical activities assists in the healthy motor development of the foot arch, gait patterns, and posture. However, overly repetitive motions may cause suboptimal alterations in mechanics such as overpronation which may occur more frequently in children due to the stage of maturation (de la Cruz, et al., 2015). Weight problems only serve to exacerbate these biomechanical pathologies. Early intervention in children has been shown to reverse deleterious gait and foot mechanics. De la Cruz et al. (2015) studied the gait patterns of 58 young athletes aged 9 to 12 years for three months. Approximately 17% had pathological gait mechanics characterized by overpronation of the heel, valgus knee alignment (knock knees), and excessive inward rotation of the hips. The children participated in a therapeutic exercise program consisting of lower body stretching and strengthening exercises. After the intervention, all participants improved their gait patterns and maintained the improvements after six months of follow-up.

Only a small percentage of patients have the rigid form, where flat feet persist regardless of foot position. Excessive pronation affects somatosensory input through changes in joint mobility, surface contact area, and muscular strategies for stability, leading to increased neuromuscular activation for balance compensation. Thus, assessing balance is crucial in evaluating foot dysfunction, as poor foot position requires postural adjustments for maintaining an upright stance and balance, especially in response to changes in surface stability (Sahin et al., 2022; Jacob, 2001).

According to Schut et al.'s findings from 2017, an increase in support surface compliance is known to increase support surface rotations and, as a result, downweighting of proprioceptive information. However, the sensitivity of sensory reweighting to changes in support surface rotation amplitude is influenced by support surface compliance itself, with less reweighting occurring on surfaces that are more compliant as support surface amplitude changes. Proprioceptive feedback during joint motion causes a significant correlation between single-leg stance time (with eyes open and closed) and flat feet. This correlation is caused by sensory information from joint receptors totaling 106 cutaneous mechanoreceptors, including 31 slowly adapting and 75 fast adapting units. The joint receptors (ligament and capsule) received divergent information from skin, articular, and muscle mechanoreceptors.

There are two primary proprioceptive receptors: slow and fast. Pacinian corpuscles are the fast receptors that quickly respond to external stimuli and sense movement. Slow receptors include Ruffini corpuscles, which sense the change of position and the accuracy of joint position. These receptors deteriorate with increasing age, affecting the single-leg stance time (Figure 2). For example, Yang et al. (2016) observed an exponential decrease in ankle complex proprioceptive acuity across young, middle, old, and very old populations. Indeed, this decline in cutaneous sensitivity contributes to increasing fall risk in aging adults.

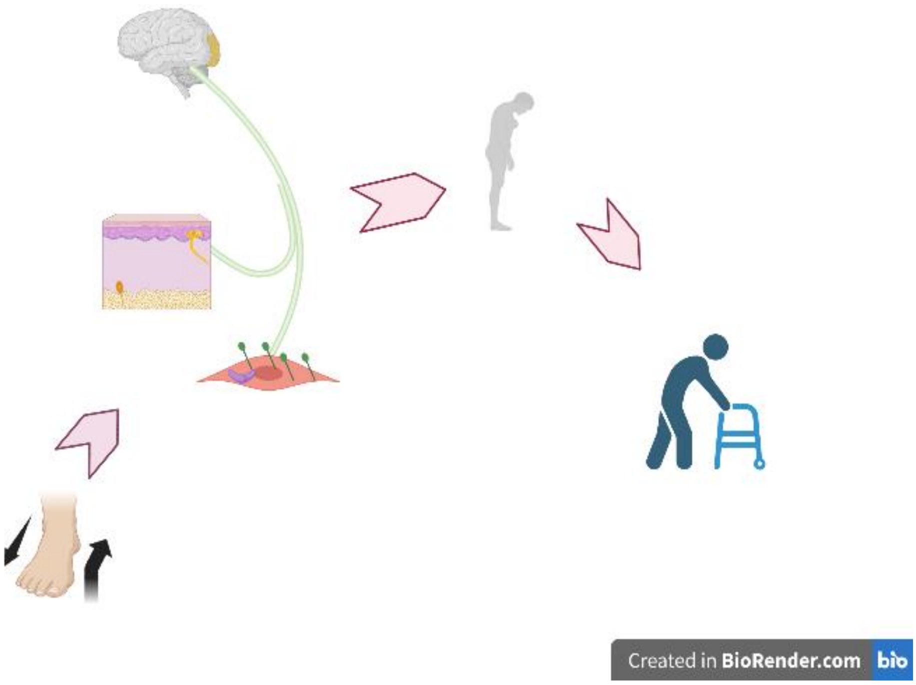

Figure 2: Illustrations explaining the relationship between foot, posture, and gait.

a. Altered foot posture.

b. change in muscle stretch angle which sends abnormal signals to the brain.

c. Affects balance.

d. Causes dependent gait.

When the heel valgus increases, it leads to imbalance due to the change in muscle stretch angles and passive elements around the joint. Because of this, the foot sends the wrong signals to the brain, which can influence balance. Additionally, because heel valgus causes the heel to have limited contact with the ground, fewer sensory receptors are involved in transmitting the necessary information to maintain balance.

Excessive pronators, who tend to collapse toward the medial aspect of the foot and have a reduced capacity to maintain rigid support in full weight-bearing, may be the cause of reduced distance in an oblique and lateral direction in flat foot patients. Pronation may be accounted for by this medial deviation and increased foot mobility, which may also reduce dynamic reach in the lateral direction. Therefore, maintaining dynamic balance necessitates greater muscle strength, neuromuscular control, and precise proprioception in the lower extremity joints (Sahin et al., 2022; Jacob, 2001; Keller et al., 1996).

The feet of obese people are constantly subjected to excessive strains to support their weight. During normal gait, the load on the feet is around 1.2 times the body weight and increments to 2-3 times the body weight while running (Hills et al., 2001). Weight-bearing on the medial longitudinal arch is approximately three times higher in obese people than it is in people of normal weight (Hills et al., 2001; Anandacoomarasamy et al., 2008). This can lead to negative biodynamic changes like high plantar pressures, which cause damage to plantar tissues during activity, which may reduce quality of life and restrict physical activity (Mickle & Stelle, 2015; Duvigneaud, et al., 2008).

Pronation of the foot because of a lower medial longitudinal arch and excessive weight bearing on the plantar fascia's origin and insertion appear to have increased plantar pressure on the first metatarsal, second metatarsal, and heel. In this study by Hills et al. the obese group had lower anterior-posterior balance and medial longitudinal arch height when standing on one foot. Antero-posterior balance is also affected by the foot's mechanoreceptors, and that also lowers the height of the medial longitudinal arch. In case of excess body weight, which can cause altered cutaneous mechanoreceptors, the threshold decreases the joint proprioception, a mandatory balance component. Obesity-related excessive foot weight bearing results in abnormal structural and functional changes in the foot. This causes several unpleasant symptoms, including muscle weakness and decreased physical activity due to imbalance while maintaining erect positions (Duvigneaud, et al., 2008).

1.3. Firefighters' Feet

Compensatory movements due to occupational hazards, repetitive movements, pro-tective gear, and externally borne equipment place adaptive pressures on the entire kinetic chain starting with the foot and ankle complex. A primary example is the firefighters. The firefighters' personal protective equipment includes a coat, pants, fire boots, gloves, hood, helmet, and self-contained breathing apparatus (SCBA) (Park et al., 2019; Sokolowski et al., 2019). Fire boots are the only means firefighters can interact with the unpredictable firegrounds, where heavy fire gear with an SBCA makes it harder for the body to balance (Sokolowski et al., 2019; Campbell et al., 2020). According to firefighters, improperly fitting fire boots negatively impact gait: Due to the large void space in their boots, their bulky boots flop around when they initiate a stance, necessitating additional kick and duck-strolling or venturing over hindrances. Over half of the people wearing fire boots that didn't fit right thought the boots were too loose overall (Park et al., 2019; Sokolowski et al., 2019).

Musculoskeletal conditions like tendinitis, plantar fasciitis, and foot structure abnormalities, such as flat feet and hammer toes, were the primary occupational dysfunctions in firefighters. Wounds connected with lower body versatility, such as falling, bouncing, slipping, and stumbling, are the second most incessant reason for wounds on the fireground among U.S. firefighters (Campbell et al., 2020).

In real-world firefighting situations, ill-fitting fire boots pose a serious safety risk due to their significant role in lower body movements. Eighty percent of female firefighters reported problems with ill-fitting fire gear, whereas only 21 percent of male firefighters reported the same issue (Campbell et al., 2020; Hsiao et al., 2014; Hulett et al., 2008).

1.4 Foot Posture and Balance in Upper-String Instrument Players

Another example of pathological compensatory mechanics is found in musicians. Assessing postural alignment and muscle activity among musicians is important because these are considered predictors of musculoskeletal injuries. Musicians are required to maintain optimal posture for standing performance, and they tend to be rigid, with a well-placed head, axis of gravity, and lower limbs. While sitting, they tend to exhibit a backward-tilted pelvis, excessive kyphosis, and head forward with a well-placed axis of gravity and lower limbs. While seated posing, they tend to exhibit a backward-tilted pelvis, excessive kyphosis, and a head-pushed forward, with a well-placed axis of gravity and no sideways head tilt, and half adopt incorrect lower limb placement. In either position, they push shoulders forward without raising or tilting them. One study reported significantly decreased electromyography activity (EMG) in the spinal musculature among violinists, suggesting ergonomic aspects of playing musical instruments with and without shoulder rest (Levy & Lee, 1992).

Baadjou et al. (2017) performed two-dimensional goniometric analysis and surface electromyography in clarinets to assess body posture and muscle activity. They found that optimal body posture promotes efficient muscle use and enhances sound production while minimizing the risk of musculoskeletal issues. This study highlights the significance of proper ergonomics in instrumental performance, particularly in clarinet, which demands precise muscle control and coordination. The findings contribute to a better understanding of the interplay between body posture, muscle activity, and musical outcomes, offering practical implications for musicians and educators to improve playing techniques and prevent performance-related injuries.

One systematic review reported the importance of ergonomic considerations among musicians in preventing musculoskeletal injuries. The authors found that appropriate posture significantly impacts musical performance and lowers the risk of musculoskeletal injuries (Chi et al., 2020). It is important to note that improper instrument set-ups during musical performance or practice could contribute to the progression of playing-related musculoskeletal disorders in violinists and pianists (Levy et al., 1992; Chi et al., 2020). Hence, thorough research on appropriate ergonomics is necessary to address musculoskeletal injuries among musical performers.

2. Corrective Exercises to Improve Posture, Balance and Gait

Mascarenhas et al. (2023) analyzed the effect of conventional proprioceptive training and game with motion monitoring. They found that both treatments were equally effective in improving plantar tactile sensitivity in older women. However, no significant differences were observed between conventional and virtual training. The conventional proprioceptive training program included warm-up (walking, stretching, and breathing exercises), gait, balance, and proprioceptive training. The virtual reality proprioceptive training exercise games were performed using Microsoft's Xbox Kinect video game (Mascarenhas et al., 2023). Sahan et al. (2021) compared the short-term effects of virtual reality and short foot exercises in pes planus. They found that both were equally effective and improved performance, balance, and navicular drop in subjects with pes planus. The short foot exercises included pulling the first metatarsal head towards the calcaneus without flexing the toes, suggesting that they could be beneficial for healthcare professionals in managing pes planus.

Further, intrinsic foot muscle strengthening exercises (IFM) are crucial in preventing pronation-related injuries. IFM includes short foot, toe posture, towel curl, and metatarsophalangeal joint muscle training. These short foot exercises are the most evident because they utilize the intrinsic foot muscles to draw the metatarsal head back towards the heel while minimizing distal interphalangeal function. Through IFM training, weakened or inhibited IFMs were activated by optimizing the tension of the medial longitudinal arch, and foot-ankle neuromuscular control was improved, which helped prevent running-related injuries (Lynn et al., 2012). Literature also suggests that dynamic balance is weaker in individuals with flat and cavus feet; therefore, IFM could be beneficial in addressing those conditions (Dabholkar et al., 2012).

Interestingly, SFEs, as opposed to TCEs, may be preferred for the rehabilitation of the decreased medial longitudinal arch. Chung et al. (2016) conducted a randomized control trial on 30 men and women and compared the effects of SFE versus TCE on the navicular drop and ankle instability via the Cumberland ankle instability test. The SFE group significantly increased ankle stability and had greater navicular drop reductions than the TCE group. The differences in the effects of these two treatments are explained by the activation of only the intrinsic foot muscles in the SFEs. In contrast, the intrinsic and extrinsic foot muscles are activated on TCEs because the compensation by the extrinsic foot muscles often presents with overpronation; further development of the extrinsic foot muscles through TCE would be counterproductive.

Kuo et al. (2022) found a positive correlation between long-term Tai-Chi-Chuan practice and whole-body balance control during obstacle-crossing in older adults. This study highlighted that Tai-Chi-Chuan significantly increased toe-obstacle clearance and a more posterior center of mass position relative to the center of pressure with smaller inclination angles and a lower rate of inclination angle change during leading-limb crossing. Therefore, this training could potentially enhance balance and improve daily mobility and fall prevention.

Evidence states that different forms and types of exercises are available to improve balance and lower limb muscle strength and prevent falls in older individuals. The Otago Exercise Program (OEP) emphasizes strength and balance training. OEP comprises four exercise modules: warm-up activities, strength training, balance training, and walking training. Studies have demonstrated the positive outcomes of OEP, such as improving balance, gait, and muscle strength and enhancing cognitive function. It's important to note that tailored exercise prescriptions are necessary for older individuals to mitigate the risk of adverse events (Yang et al., 2022; LuiAmbrose et al., 2021).

3. Highlights

- Due to its flexible and rigid structures, the human foot greatly contributes to body balance, weight support, and shock absorption. Therefore, the foot muscles play an important role in maintaining postures and balance.
- Plantar sole and ankle complex proprioceptive feedback is of primary importance for maintaining balance and postural stability. Hence, changes in foot posture influence neuromuscular control and proprioceptive acuity primarily in older adults.
- Pes planus or flat foot, where the medial arch is flattened, changes the sensory input and alters muscle activity, hence affecting balance and gait. This is especially relevant in athletes and the obese.
- Occupational and task-based demands are exemplified in firefighters and musicians, with poorly fitting equipment and prolonged postures contributing to musculoskeletal problems.
- There is some evidence that proprioceptive training and intrinsic foot muscle exercises are potentially beneficial for improving foot posture, balance, and gait, specifically in conditions like pes planus and older adults.

4. Conclusion

This review found a significant correlation between foot posture, balance, and gait. It gives us insight into the importance of maintaining correct foot posture by wearing appropriate-fitting and correct-type shoes in various professions. Additionally, enhancing our understanding of foot posture and balance could offer valuable insights for healthcare professionals seeking potential solutions.

5. Limitations and Future Recommendations

This study elucidates a possible mechanism for improving balance and gait by improving foot posture. It also explains different forms of exercise that can help improve foot posture, balance, and gait. Future studies may help reveal the pressure caused by the abnormal versus normal foot. This also helps recognize the severity of postural disorder and increases awareness of proper footwear. This explanation will help to choose appropriate exercise options and alternative therapies to improve balance and gait in postural disorders.

6. Conflicts of Interest

The authors declare no conflicts of interest.

6.1. Authors Contribution

Conceptualization and draft preparation, PSG and B.P, reviewing and editing, A.E, PSG, and B.P. All authors have read and agreed to the published version of the manuscript.

6.2. Funding

This study received no funding

6.3. Clinical Trial Number

Not applicable

6.4. Ethics Declarations

- Consent for publication
  Not applicable
- Availability of data and materials
  Not applicable
- Competing interests
  The authors declare no competing interests
- Ethics approval and consent to participants
  Not applicable

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