

Research on Foot Function Adaptation and Injury Prevention from the Perspective of Sports Biomechanics

Junxi Luo *

Ulink College of Beijing, Beijing, China

* Corresponding Author Email: 273362825@qq.com

Abstract. Due to frequent exercise during the offseason, some damage has developed in the structure and function of the feet, and the risk of overuse injuries in sports has increased. Systematically explore the functional adaptation characteristics, biomechanical mechanisms, and dialectical relationship with injury risk in the three areas of the midfoot, lateral foot and heel from the perspective of sports biomechanics in this study. The three levels of the damage prevention framework in this paper are training interventions, equipment interventions and monitoring and evaluation. This paper provides a theoretical basis for the regional-specific patterns and bidirectional effects of functional adaptation, offering evidence-based support for training load planning, shoe design and scientific management of injury risk in practice.

Keywords: Sports biomechanics, plantar pressure, functional adaptation, injury prevention.

1. Introduction

With the continuous development of competitive sports, the demands on the biomechanics of the feet in competition for athletes have gradually been increasing. As the sole support between the human body and the ground, the feet need to perform all sorts of functions in different dynamic conditions, such as bearing the full weight of the body, generating forward and lateral thrust, adjusting the body's posture, making emergency stops, etc. Competitive sports are special exercises with many directions, high speeds and high intensity, and thus the mechanical demands on the feet differ in terms of load level, frequency of action, and direction of action [1][2]. Plantar pressure is a representative biomechanical index for assessing the functional load status of the foot quantitatively, and it can show the distribution, maximum value and load-bearing characteristics of different areas in the foot under static and dynamic states. Through plantar pressure analysis, more information can be obtained about the mechanical working conditions of the foot in various movement states; at the same time, abnormal load distribution and injury risks can be identified, and thus training strategies or equipment designs based on scientific research can be developed [3]. Therefore, research on the biomechanics of the foot based on plantar pressure data has gradually been conducted in sports science [4].

Systematically explore the mechanism by which foot function is adapted through extended exercise training from a sports biomechanics perspective; identify the interdependence of adaptation and injury, provide theoretical support for injury prevention and training optimisation, and offer new ideas for shoe design. Build an entire logical chain in this paper from biomechanical mechanisms to practical applications, and hope to help promote the long-term health and performance enhancement of athletes.

2. Biomechanical Basis of Foot Functional Adaptation

The three functional Areas of a person's foot in terms of mechanics are the forefoot, midfoot and hindfoot. At the beginning of the push-off stage in late-stage walking and running and jumping, the forefoot bears a substantial load. The arch of the foot serves as a load-bearing part in the middle of the foot to distribute the vertical ground reaction force to the forefoot and hindfoot, and to maintain the longitudinal stability of the foot. The heel is a heel bone and a thick layer of subcutaneous fat; it is the first part of the foot to contact the ground during walking. This part is to bear a large impact load, so it has been designed accordingly. When a foot is under load, the arch of the foot undergoes

a slight deformation to store elastic potential energy, and at the same time, this energy is released for propulsion during the ground-release phase; simultaneously, the plantar fascia functions as a "truss" to keep the stability of the arch shape and prevent excessive collapse or elevation. The three zones in a collaborative structural design serve different functions of the foot in different ways during movement, such as weight-bearing, cushioning, stability and propulsion [5].

The bottom of the foot bears some load from walking and running; it has been named the plantar surface. Different kinds of exercise have different mechanical demands on the foot, and thus the distribution in regions, peak values and time-of-day patterns of plantar pressure will also vary periodically. Among all the plantar pressure parameters, the three most commonly studied are peak pressure, centre of pressure trajectory and load transfer. All of the above indicators can be used to assess the biomechanical work status of the foot in different movement modes comprehensively.

Long-term and systematic exercise training can induce multi-level structural and functional adaptations in the feet; these are active responses by the body to repeated mechanical stimulation. Strengthening of the muscles, ligaments and bones in the foot and other parts of the body will be undertaken. With repeated weight-bearing and force training, both the cross-sectional area and contraction strength of the intrinsic and extrinsic muscles in the foot increase gradually; thus, the active control ability of the foot under dynamic loads is enhanced. Periodically applying tension stimulation causes the collagen fibres in the plantar fascia and ligaments of the foot to organise more regularly, thereby increasing tensile strength and improving the static and dynamic stability of the arch. Long-term load stimulation leads to bone density changes in the skeletal system via Wolf's law, causing thickening of cortical bone and trabecular remodeling, which strengthens the fracture resistance of weight-bearing bones such as the calcaneus and metatarsals. Long-term training has significantly improved the stability control and movement-response speed of the feet at the neuromuscular level. The closer the training content is to a particular mode of operation, the more pronounced the adaptation effect will be in that mode. Although the reinforced structure has improved performance, a long-term heavy-duty load at a single point may still cause damage due to wear and tear [6].

3. Functional adaptation characteristics of three key areas of the foot

3.1. Mid Foot Region

The midfoot mainly plays a passive shock absorption role in the daily activities of the general population. Due to the linear forward movement of daily exercise, the midfoot only bears about 12%-15% of the total plantar pressure, and the arch of the foot mainly disperses vertical impact force through elastic deformation. However, athletes who have been engaged in high-intensity, multi-directional sports training for a long time exhibit significant changes in their mid-foot pressure characteristics: peak pressure increases by about 42% compared to the general population, and this increase is task dependent - the difference is not significant during low-intensity activities, but sharply increases during high-intensity dynamic tasks. In addition, athletes often exhibit asymmetry in the dominant side of their limbs, with the non-dominant side bearing higher loads in the middle of the foot, reflecting their ability to undertake more stable compensatory functions in multi-directional movements. From the perspective of biomechanical mechanisms, the core change in the midfoot is the transition from passive shock absorbers to active force transmitters. Long term training promotes structural strengthening of the midfoot muscles and ligaments, leading to faster dynamic regulation of the neuromuscular system. In a state of fatigue, a decrease in neuromuscular control can lead to pressure concentration towards the medial midfoot, further increasing the risk of local overload.

3.2. Lateral Foot

The lateral aspect of the foot has extremely limited functional contribution in the daily movements of the general population. Due to the predominance of sagittal movement in daily activities and rare lateral loads, the total plantar pressure contributed by the lateral foot is less than 10%, providing limited anti inversion stability only during passive landing. After long-term engagement in sports training with lateral movement requirements, the lateral foot is forced to transition from a passive stabilizer to a core support zone and force application zone. Data shows that the peak pressure on the lateral side of athletes' feet is about 37% higher than that of the general population, with 65% -70% of the load concentrated on the 5th metatarsal bone. From the perspective of biomechanical mechanisms, this functional remodeling originates from training-induced structural reorganization: repeated lateral load stimulation leads to a significant increase in the density of the 5th metatarsal bone, and the activation level of the lateral foot stabilizing muscle group (such as the peroneal muscle) is also significantly increased. This series of adaptations enables the lateral foot to meet the dual needs of lateral stability and lateral force application, but also exposes it to specific injury risks.

3.3. Heels

The heel is designed as a natural impact absorbing core in the general population. The heel bone, combined with a thick subcutaneous fat pad, forms an efficient shock absorption mechanism. The heel pressure of the general population during jogging usually does not exceed 200 kPa, which is considered the biomechanical safety threshold for non exercise populations. However, athletes who have been engaged in jumping landing cycling exercises for a long time have heels that far exceed this safety boundary in dynamic tasks, with dynamic peak pressure reaching more than 2.6 times that of the general population jogging, and often exhibit a strategic choice of prioritizing landing with the posterior outer heel. From the perspective of biomechanical mechanisms, this extreme load comes from the superposition of two factors. Firstly, the take-off landing cycle generates an impact force of up to 3-5 times body weight, with the heel being the first point of contact; Secondly, long-term explosive power training further enhances the ability to generate lower limb strength, resulting in greater impact force when landing. The high dynamic load on the heel is not a technical defect, but an inevitable performance injury trade-off in high-level athletic performance.

4. Dialectical Relationship Between Functional Adaptation and Injury Risk

The adaptation of foot function induced by long-term exercise training not only significantly improves athletic performance, but also inevitably increases the risk of specific injuries. From the perspective of performance improvement, after structural strengthening and neuromuscular adaptation, the weight-bearing capacity of various areas of the foot is significantly enhanced, stability control is more precise, and impact absorption efficiency is greatly improved. These changes enable athletes to perform technical movements that are difficult for ordinary people to achieve in complex movements with high intensity, high speed, and multiple directions. However, from the perspective of increased risk, these adaptations come at the cost of chronic tissue overload: in order to obtain stronger force transmission capabilities, the midfoot bears higher compression and shear stresses; In order to obtain better lateral stability support, the lateral side of the foot, especially the 5th metatarsal bone, is in a long-term high load state; In order to withstand greater impact on the ground, the heel tissue is repeatedly exposed to pressure environments far beyond physiological safety thresholds. More importantly, when athletes are in a state of fatigue, local tissues that are already on the edge of high load will further lose precise control of the neuromuscular system, thereby transforming potential overload risks into actual injury events.

The functional adaptation directions of the three key areas of the foot are different, and accordingly, their specific injury risks also show significant regional differentiation as shown in Table 1.

Table 1. Functional adaptation directions and specific injury risks in the three distinct regions of the foot

Region	Primary Adaptation	Potential Injury
Midfoot region	Enhanced force transmission	Plantar fasciitis, ligament injury, tarsal stress fractures
Lateral foot	Stabilization of lateral side	Peroneal tendon lesion, 5th metatarsal stress fracture, ankle sprain
Heel	Enhanced impact absorption	Heel pain, Achilles tendon disorders, plantar fasciitis

In a non fatigue state, the neuromuscular system of athletes' feet can accurately regulate the pressure distribution in various regions, allowing high loads to be reasonably distributed between the midfoot, lateral foot, and heel, thereby avoiding local tissue overload while exerting adaptive advantages. However, with the prolongation of exercise time and the deepening of fatigue, the ability of neuromuscular control will significantly decrease, manifested as slower muscle response speed, reduced coordination, and weakened perception and regulation of changes in plantar pressure. This decrease in control ability directly leads to an unfavorable redistribution of plantar pressure. Fatigue management should not be viewed solely as a matter of athletic performance, but should be included as a core consideration in injury prevention

5. Injury Prevention Strategies and Applications

5.1. Intervention at the Training Level

The base for preventing foot injuries is training, and its content should aim to improve the active stability of the foot by conducting focused training rather than being passively supported externally. The two types of muscle strength training for the foot are the intrinsic foot muscles and the fibular muscle group. The intrinsic muscles in the foot support the arch and can strengthen them to increase the height and dynamic stability of the arch. Oliveira and others have determined that exercise training of the intrinsic muscles can increase the range of motion for extension at the metatarsophalangeal joints of the foot significantly[7].

The other two are fatigue management and load monitoring of the training intervention. Fatigue impairs the precision of neuromuscular control and, as a result, shifts the distribution of plantar pressure abnormally. Chen and others have built a wearable plantar pressure system and used surface electromyography to study the effects of muscle fatigue on plantar pressure systematically [8]. Fatigue has reduced the peak pressure at the heel and increased the pressure of the metatarsal heads. At the same time, the median frequency of the surface electromyographic signal for the gastrocnemius muscle is also significantly lower. The above changes show that, in fatigue, the distribution of load transfer has shifted from the heel to the forefoot. Simon and others conducted a field study and found that after 3 hours of continuous work, there was a considerable change in the distribution of plantar pressure, and a regular difference had appeared between the right and left feet [9].

Based on this, in practice, heart rate monitoring combined with subjective fatigue rating (RPE) can be used for load quantification, and real-time monitoring can be carried out through wearable underfoot pressure devices. When abnormal pressure increases in specific areas or the variability of pressure center trajectories exceeds 20% of the individual baseline, rest or reduced intervention should be initiated in a timely manner.

5.2. Intervention at the Equipment Level

Intervention at the equipment level achieves active redistribution of plantar pressure through external support systems, thereby reducing the risk of local tissue overload. The study by Wu Shuxia et al. used finite element analysis to systematically evaluate the effect of total contact insole on plantar pressure [10]. The results showed that the stress on the sole of the shoe after wearing a full contact insole was not only more evenly distributed than that of a regular insole, but also showed a significant decrease overall. The contact area in the arch area increased, and the local high-pressure area was effectively transferred. The study further found that insoles made from a combination of medium Plastazote, MicrocelPuff, and Neoprene cream solution had the best effect in reducing plantar pressure, providing a material science basis for zone optimization design.

The core goal of insole design is pressure redistribution and local peak reduction. The optimization strategy based on finite element analysis indicates that an ideal insole should have the following characteristics: using high-density, high rebound materials in the heel area to enhance impact absorption capacity; Using moderately hard support materials in the middle of the foot to maintain arch shape; Use softer materials on the forefoot and lateral side of the foot to increase contact area and disperse pressure. In practice, a plantar pressure mapping system can be used to dynamically detect the pressure distribution of individuals. Based on the detection results, customized insoles can be made through computer-aided design and manufacturing technology to achieve true "pressure guided design". In addition, the overall structural design of footwear should also be coordinated with regional optimization: the height and stiffness of the shoe upper affect ankle stability, the curvature and hardness of the sole affect kicking efficiency, and the breathability and wrapping of the shoe upper material affect the comfort and fatigue process of long-term exercise. The organic combination of equipment intervention and training intervention is currently the mainstream direction of evidence-based injury prevention.

5.3. Monitoring and Evaluation

Monitoring and evaluation provide the technical support for scientific damage prevention, and their main purpose is to shift from "judgment based on experience" to "decision-making based on data". Both static and dynamic tests will be carried out; In the static test, bare feet standing and natural standing will be performed to evaluate the distribution of pressure and bipedal symmetry at rest, and dynamic tests will include natural walking, jogging and other special exercises to obtain indices such as peak pressure, pressure time-integration, and the trajectory of the pressure center during movement.

Biomechanics of the fatigued state serve to bridge the gap between laboratory experiments and in-situ motion. Vallecabres and others found that after fatigue-induced exercise programmes in simulation, the midfoot pressure increased by about 20% and was associated with medial displacement. Based on the above analysis, fatigue-state assessment can be added to the regular monitoring [11].

6. Conclusion

Through sports biomechanics, this paper systematically explores how changes in the foot function resulting from extended specialized training are related to the risk of injury. More research has found that the main regulatory function of the fatigue state is to redistribute stress, and an integrated, multi-level damage prevention system comprising training intervention, equipment design, and monitoring and evaluation has been established. This paper shows that adaptation and injury are in a dialectical relationship, and therefore provides evidence-based support for training-load planning zoning optimisation in shoe design and data-driven fatigue management. In the future, research will be conducted on the adaptive time course and reversibility of longitudinal tracking design, and wearable sensors and artificial intelligence algorithms will be used to achieve real-time warning of individual injury risks.

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