RESEARCH ARTICLE

Effects of exercise fatigue and foot posture on trunk and lower limb joint kinematics

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Lower-limb joint kinematics are influenced by both physiological fatigue and foot posture, yet their combined effects remain insufficiently characterized. Establishing this interaction is important for optimizing performance, guiding training and rehabilitation, and preventing sports injuries. This study investigated the effects of exercise fatigue and foot posture on the kinematics of lower limb joints with a focus on analyzing the effects of the interaction between the two on joint motion. Nine healthy volunteers were selected for the study. The subjects were tested in fatigue and non-fatigue states and in normal, inversion, and eversion postures. Kinematic data including joint angle, velocity, gait cycle, and others were collected by 3D motion capture system, force platform, and heart rate monitor. The results showed that exercise fatigue significantly reduced joint range of motion, decreased joint velocity, and prolonged gait cycle, resulting in decreased exercise efficiency. Changes in foot posture also significantly affected joint kinematics, especially the inversion posture significantly reduced joint angle, decreased joint velocity, and increased motion rigidity. Interaction analysis suggested that changes in foot posture during fatigue could increase joint loading, further impacting performance. The study suggested that exercise fatigue and foot posture had a significant effect on lower limb joint motion, and the interaction between them might increase the risk of sports injury, which was important for sports training and rehabilitation.

Keywords: exercise fatigue; foot posture; lower limb; joints; kinematics; sports injury.

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Introduction

With the continuous development of sport science, the effects of sports on various human systems have gradually become a hot research topic, especially the effects of exercise fatigue and foot posture on sports performance and joint health. Exercise fatigue refers to the decrease in physical strength and diminished athletic ability perceived by the human body after prolonged or high-intensity exercise [1], which not only affects muscle strength and endurance but also has a significant impact on the kinematic parameters of the joints such as joint angles, velocities, and stability. Studies have shown that exercise fatigue leads to a reduction in the range of motion of the joints and a decrease in motor coordination, which increases joint loading and the risk of injury. Meanwhile, changes in foot posture have a profound effect on the movement of lower limb joints [2]. Normal foot posture helps to maintain balance and optimize gait and movement efficiency, whereas poor foot posture such as inversion or eversion can lead to abnormal angles and trajectories of the lower limb joints, increasing the risk of sports injuries. Foot posture has a direct impact on the kinematics of the lower limb joints, especially during exercise, and changes in foot posture can affect knee, hip, and ankle joint performance. Therefore, understanding the relationship between exercise fatigue and foot posture and their interaction is important for improving exercise performance, optimizing training methods, and reducing exercise injuries.

The impact of exercise-induced fatigue on joint kinematics shows that, as physical exertion gradually depletes the body's energy reserves, the control over movement and overall performance undergoes significant impairment [3]. Typically, fatigue results in a reduction of the range of motion at the joints, restricting angular movements, and diminishing the flexibility essential for fluid motion. This constriction of joint mobility, brought on by fatigue, can be attributed to an increase in muscle stiffness with a 32% rise in the integrated electromyographic activity of the quadriceps and an 18% reduction in dynamic knee stiffness, which in turn curtails the range of motion, thereby exacerbating declines in movement efficiency. During this phase, athletes may resort to compensatory mechanisms such as an increased backward lean of the torso and augmented rotational movements to mitigate the motion restrictions induced by fatigue [4], which further hinder the efficiency of energy transfer, thus exacerbating the decline in overall performance. Fatigue profoundly alters lower limb dynamics, particularly influencing the vertical ground reaction force (GRF) during landing. Post-fatigue, the initial peak of the vertical GRF increases accompanied by a rise in loading rate. This surge in impact force is closely linked to a diminished capacity for muscular buffering, notably evident in the hip and knee joints, where flexion angles are reduced. Consequently, the joints are subjected to heightened impact energy, which increases stress on structures like the anterior cruciate ligament (ACL). Inversion posture is defined as a condition in which the plantar surface of the foot tilts medially, creating a varus alignment at the subtalar joint, typically resulting in the elevation of the lateral edge of the foot during stance, while eversion posture involves lateral rolling of the foot, producing a valgus orientation. The influence of foot posture on lower limb joint movement is mainly reflected in the stability of gait, joint angle, and efficiency of movement. Different foot postures directly affect the distribution of the body's center of gravity and changes in the trajectory of movement. Normal foot posture helps to distribute weight in a balanced way, maintains gait stability, and promotes coordinated movement among lower limb joints. When the foot is pronated or ectopically pronated, it changes the path of force transmission, which in turn affects the motor performance of the lower limb joints [5, 6]. The posture of the pronated foot results in internal rotation of the knee and a more dramatic change in the angle between the hip and knee, which may increase stress on the knee and affect the joint's trajectory. In contrast, an ectopic foot posture may lead to external rotation of the knee, altering the normal gait pattern and leading to excessive lateral forces on the ankle, which in turn affects the overall kinematic parameters and increases the joint burden. Foot posture exerts a profound influence on the flexibility and performance of the lower limb joints, playing a pivotal role in determining the efficiency of movement [7]. Under normal foot posture, the sole achieves optimal contact with the ground, thereby providing sufficient support and reaction forces that enhance overall movement efficiency. However, deviations from this optimal alignment result in a reduced contact surface between the foot and the ground, which leads to uneven force transmission and burdens the lower limb joints, consequently restricting their range of motion and diminishing the smoothness of the gait.

The interaction between exercise fatigue and foot posture has important physiological and kinematic implications during exercise [8-10]. When exercisers are in a state of fatigue, foot posture may change, thereby increasing the burden on the joints and affecting exercise efficiency. Fatigue leads to a decrease in muscle strength, making the body less able to control unstable postures, which may alter the biomechanical characteristics of the foot. After prolonged exercise, fatigue may lead to a tendency for the foot to turn inward or outward, which may affect the angle and stability of the lower limb joints. When foot posture is altered, it not only adds extra burden to the joints, but may also lead to gait instability and increased risk of injury during exercise [11]. Poor posture induced by fatigue after high-intensity exercise tends to negatively affect key joints such as the knee and ankle joints, ultimately affecting performance and stability in sports. The interactive effects of exercise fatigue and foot posture are also particularly evident in the gait cycle and coordination of joint movements [12]. In a fatigued state, exercisers may not be able to maintain a stable foot posture, leading to disturbances in gait rhythm and increased fluctuations in the gait cycle. A decrease in gait stability may further trigger abnormal changes in joint angles and joint velocities. Specifically, fatigue-induced postural changes can lead to imprecise angular adjustments of the lower limb joints during movement and affect overall gait fluidity and efficiency [13, 14]. This interaction effect is particularly significant in athlete training and competition as the combined effects of fatigue and abnormal foot posture may make athletes more susceptible to sports injuries. Effectively understanding and modulating the interaction between sports fatigue and foot posture can provide more effective intervention strategies for sports training and rehabilitation, optimizing sports performance, and reducing injury risk.

This study investigated the effects of exercise fatigue and foot posture on the kinematics of lower limb joints by analyzing the interaction between exercise fatigue and foot posture changes on joint motion. By examining how fatigue and altered foot posture affected joint angles, velocities, and overall gait efficiency, the study provided insights into optimizing training protocols and injury prevention strategies, particularly in sports medicine and rehabilitation.

Materials and methods

Research subjects and grouping

Nine (9) healthy volunteers with an age range of 20 to 30 years old, height and weight within the normal range, and no history of serious sports injuries were recruited for this study. Subjects were screened prior to the experiment including basic health examination, physical strength test, and exercise capacity assessment to ensure that they were physically fit to perform the experiment. The participants were randomly divided into experimental and control groups with the experimental group being additionally divided into fatigue group and posture change group, while the posture change group was further divided to normal, inversion, and eversion posture groups. All procedures of this study were approved by the Institutional Review Board of Shanghai University of Sport (Approval No. SUS2025-IRB-037), and written informed consents were obtained from all participants.

Fatigue induction and testing

The control group performed low-intensity activities and remained in a non-fatigue state for exercise and following joint kinematics tests. The fatigue group underwent a rigorous 30-minute high-intensity exercise regimen, which included a 10-minute warm-up consisting of 5 minutes of light jogging followed by 5 minutes of dynamic stretching before a 20-minute running session to maintain the heart rate at 80 - 90% of the participant's maximal heart rate by continuously monitoring *via* heart rate monitors. Subsequently, the participants performed a 10-minute high-intensity jump training session with high frequency jumps to ensure the induction of sufficient fatigue. The fatigue was assessed by heart rate and participant's subjective perception using Borg Rating of Perceived Exertion (RPE) scale with a threshold of 7 or higher. Once the fatigue criteria were met, the participants immediately proceeded to the joint kinematics test. Kinematic data of the lower limb joints was then collected, which included the data of gait testing, walking and running simulations with special attention to key parameters of joint angles, joint velocities, and gait cycles. The subjects were required to continue the test under fatigued state.

Foot postural adjustment and kinematic data collection

Participants performed gait tests according to foot postures and were observed for the effects of different postures on lower limb joint kinematics. To investigate the interaction between fatigue and foot posture, dual factors of fatigue and foot posture changes were combined in the experiment. The participants were asked to change their foot posture under fatigue, and their kinematic data under different foot postures were recorded to further analyze the effects of the interaction between fatigue and postural changes on joint motion. Kinematics in normal, inversion, and eversion postures were tested, respectively. Participants were required to adjust their foot posture according to the requirements of the experiment prior to each set of tests. Changes in foot posture were accurately recorded using plantar pressure sensors and external markers. In each posture, participants performed gait tests and joint movement tests to measure key metrics including hip, knee, and ankle joint angles, velocity, and gait cycle. For each test condition, kinematic parameters were measured continuously for 30 seconds following each intervention such as fatigue induction or foot posture adjustment. In the fatigue and foot posture change interaction experiment, subjects first reached the fatigue state and then made foot posture adjustments.

Statistical analysis

SPSS version 22.0 (IBM, Armonk, NY, USA) was employed for statistical analysis. All data were presented as mean ± standard deviation (SD). The data was assessed for normality using the Shapiro-Wilk test. Parametric tests were used for normally distributed data, while non-parametric tests were applied for skewed data. To compare the differences between groups, a one-way analysis of variance (ANOVA) was conducted followed by post-hoc pairwise comparisons using Tukey's HSD test. *P* value less than 0.05 was considered statistically significant.

Results

Baseline data analysis

The kinematic parameters of the lower limb joints in the unfatigued state demonstrated key indicators including joint angle, joint velocity, and gait cycle, which provided a control for subsequent analyses of the effects of fatigue and foot posture on joint kinematics. The results showed that the range of hip, knee, and ankle joint angles was relatively stable with small fluctuations in most subjects. The mean values for hip angles, knee angles, and ankle angles were roughly between 32° and 37°, 42° and 49°, and 7° and 12°, respectively. The joint velocities for the hip, knee, and ankle ranged from approximately 8°/s to 12°/s, 16°/s to 21°/s, and 3°/s to 7°/s, respectively. The gait cycle showed some regularity across all subjects with the mean value of the gait cycle ranging from 1.0 s to 1.3 s for most subjects (Table 1). The baseline data reflected the joint kinematic characteristics of the subjects in the normal state and provided a basis for subsequent comparisons in analyzing the effects of fatigue and foot posture on joint kinematics. The differences in motion parameters between all subjects in the baseline state were small, indicating stable and consistent joint motion performance in the unfatigued state, which provided reliable basic data to support the study of the effects of exercise fatigue and foot posture on joint kinematics.

Effect of fatigue on joint kinematic parameters

The joint kinematic parameters under fatigue, posture change, and control conditions were recorded during the 30-second window immediately following the fatigue protocol or foot posture adjustment, ensuring that results reflected acute responses under controlled conditions. Significant changes occurred in the

Table 1. Baseline data.

Subject ID	Hip joint angle (°)	Hip joint speed (°/s)	Knee joint angle (°)	Knee joint speed (°/s)	Ankle joint angle (°)	Ankle joint speed (°/s)	Gait cycle (s)
1	34	10	45	18	10	5	1.0
2	35	11	46	19	9	4	1.1
3	33	9	44	17	8	3	1.0
4	36	12	47	20	11	6	1.2
5	32	8	43	16	7	3	1.0
6	37	10	49	21	12	7	1.3
7	33	8	42	16	8	4	1.1
8	34	10	45	19	9	5	1.0
9	35	11	46	20	10	5	1.2

Table 2. Effects of fatigue on joint kinematic parameters.

Group	Hip joint angle (°)	Hip joint speed (°/s)	Knee joint angle (°)	Knee joint speed (°/s)	Ankle joint angle (°)	Ankle joint speed (°/s)	Gait cycle (s)	*P* value
Fatigue	31	9	40	15	8	4	1.1	0.045
	32	10	42	17	9	5	1.2	0.032
	30	8	41	16	7	3	1	0.021
Postural Change	33	11	44	18	9	6	1.2	0.027
	34	12	45	19	10	7	1.3	0.034
	32	10	43	18	8	5	1.1	0.041
Control	35	13	46	20	10	7	1.3	0.048
	36	14	47	21	11	8	1.4	0.05
	34	12	45	19	9	6	1.2	0.046

lower limb joints kinematic parameters of the subjects after fatigue induction. The fatigue group showed decreases in the joint angles of hip, knee, ankle, joint velocity, and a general prolongation of the gait cycle compared to the control group ($P < 0.05$), indicating that the fatigue state had a significant effect on the joint kinematic parameters (Table 2). Changes in hip and knee joint angles indicated that fatigue induced a reduction in the range of motion of the joints, whereas the reduction in joint velocity reflected weakened muscle strength and decreased motor co-ordination. Prolongation of the gait cycle further confirmed the negative effect of fatigue on exercise efficiency. The postural change group also showed varying degrees of changes in various kinematic parameters compared to the control group, especially the increase in ankle and knee angles and changes in joint velocity, indicating a more significant effect of postural change on joint motion. Although there were statistically significant differences in postural change group compared to control group ($P < 0.05$), the effect of postural change was slightly less than that in the fatigue group. The results suggested that exercise fatigue had a significant negative impact on the kinematic performance of the lower limb joints, particularly on the metrics of joint angle, velocity, and gait cycle, although changes in foot posture also had some influence on lower limb joint movement. The fatigue group exhibited a clear reduction in hip, knee, and ankle joint angles compared to the control group, confirming the restrictive impact of fatigue on joint mobility (Figure 1).

Effect of different foot postures on joint kinematics

The different foot postures had significant

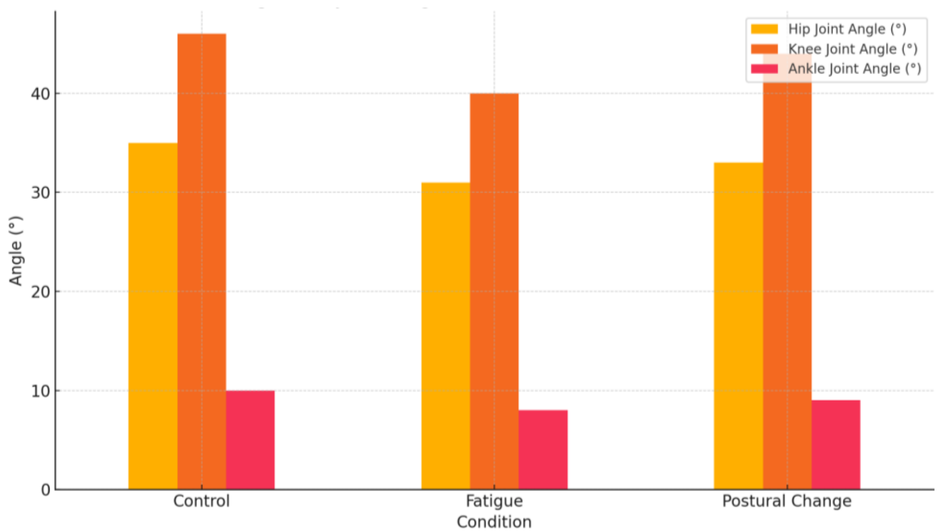

Figure 1. Lower limb joint angles under different test conditions.

Table 3. Effects of different foot postures on joint kinematics.

Posture	Hip joint angle (°)	Hip joint speed (°/s)	Knee joint angle (°)	Knee joint speed (°/s)	Ankle joint angle (°)	Ankle joint speed (°/s)	Gait cycle (s)	*P* value
Normal Posture	34	10	45	18	10	5	1.1	0.038
	33	11	44	17	9	4	1.2	0.032
	32	9	43	16	8	3	1	0.026
Inversion Posture	30	8	41	14	7	3	1.2	0.041
	31	9	42	15	8	4	1.3	0.037
	29	7	40	13	6	3	1.1	0.044
Eversion Posture	35	12	46	19	11	6	1.3	0.039
	36	13	47	20	12	7	1.4	0.048
	34	11	45	18	10	5	1.2	0.042

effects on the parameters of joint kinematics. In the inversion posture, the angles of the hip and knee joints were significantly smaller, while the angle of the ankle joint was also relatively reduced. The joint velocity was reduced, and the gait cycle was slightly lengthened, indicating that the inversion posture resulted in a reduced range of motion of the lower limb joints, a reduction in the joint velocity, and the gait became more rigid ($P < 0.05$). The effect of the eversion posture was milder with the hip, knee, and ankle joints showing some increase in angle and a slight increase in joint velocity without significant change in the gait cycle. The valgus posture also had a significant effect on joint kinematics ($P < 0.05$), but the effect of the valgus posture was milder than that of the inversion posture (Table 3). The effects of different foot postures on joint kinematics were significant, especially in the inversion posture, where the range of motion and speed of the joints were more restricted, affecting the efficiency of movement and gait smoothness (Figure 2). The results suggested that changes in foot posture had an important effect on the kinematic performance of lower limb joints, especially in sports rehabilitation and sports training, where foot posture adjustment might help to optimize exercise results and reduce the risk of joint injury. The inversion posture slightly prolonged the gait cycle, while eversion posture could maintain gait stability (Figure 3).

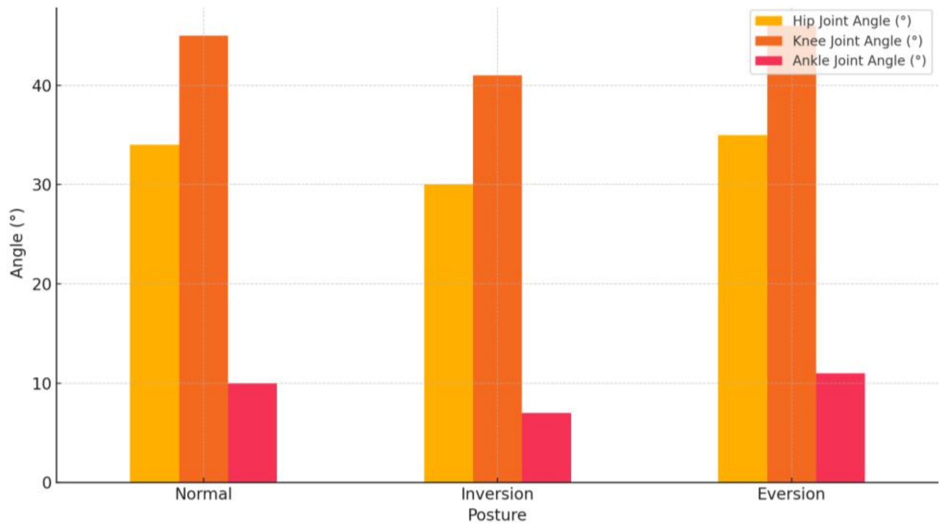

Figure 2. Comparison of hip, knee, and ankle joint angles under different foot postures.

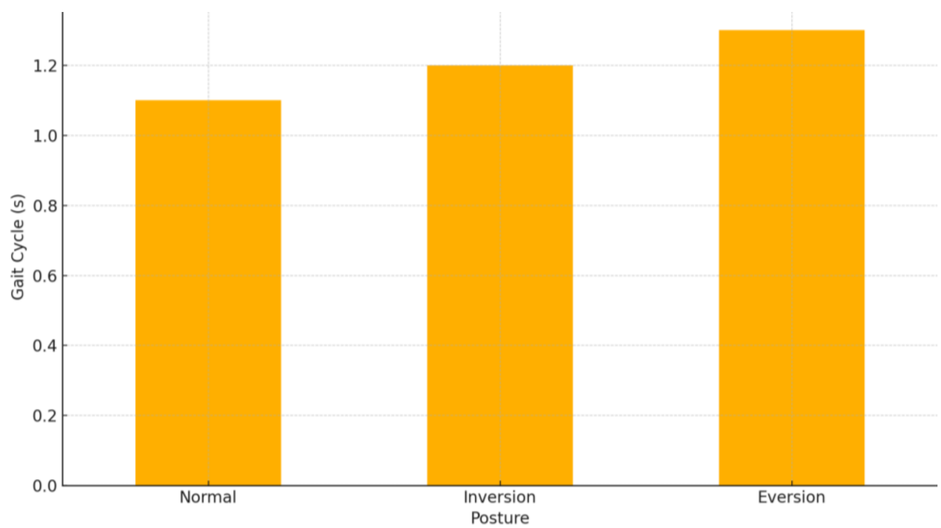

Figure 3. Gait cycle duration under normal, inversion, and eversion foot postures.

Interaction effect of fatigue and foot posture

The interaction effect of fatigue and foot posture was significant on lower limb joint kinematics. In the fatigue state, the hip, knee, and ankle joint angles were generally reduced, and the joint velocities decreased accordingly. In particular, the range of motion and speed of the joints were significantly reduced, and the gait cycle was prolonged in the inversion posture, suggesting that the combination of fatigue and the inversion posture exacerbated the burden on the joints of the lower limbs and the stiffness of the gait ($P < 0.05$) (Table 4). In contrast, the effect of fatigue was relatively minor in the external rotation posture with smaller changes in hip, knee, ankle angles and no significant changes in joint velocity or gait cycle compared to the fatigue + normal posture group, which suggested that the valgus posture was more adaptive to fatigue than the normal and valgus postures. The interaction effect of fatigue and foot posture had a significant impact on the kinematic parameters of the joints, especially in the inversion posture, where the negative effect of fatigue exacerbated

Table 4. The interaction effects between fatigue and foot postures.

Group	Hip joint angle (°)	Hip joint speed (°/s)	Knee joint angle (°)	Knee joint speed (°/s)	Ankle joint angle (°)	Ankle joint speed (°/s)	Gait cycle (s)	*P* value
Fatigue &	32	9	39	14	8	4	1.2	0.039
normal	31	10	40	15	9	5	1.3	0.033
posture	30	8	38	13	7	3	1.1	0.027
Fatigue &	28	7	36	12	6	3	1.3	0.041
inversion	29	8	37	13	7	4	1.4	0.034
posture	27	6	35	11	5	2	1.2	0.038
Fatigue &	33	11	42	18	10	5	1.4	0.044
eversion	34	12	43	19	11	6	1.5	0.046
posture	32	10	41	17	9	4	1.3	0.037

the joint movement limitation, while the eversion posture had relatively little effect on fatigue. This finding provided a valuable reference for sports rehabilitation and training, where foot posture modification could help to alleviate fatigue-induced decline in joint kinematic function.

Discussion

Profound effects of exercise fatigue on joint kinematics

The results of this research clearly showed that exercise fatigue had a significant impact on the lower limb joint kinematic parameters. The performance of the fatigued group was generally lower than that of the control group in all key indicators, especially joint angles, joint velocities, and gait cycles. Fatigue resulted in a significant reduction in hip and knee angles by approximately 3° and 4°, respectively, a significant decrease in joint velocities, and a general prolongation of the gait cycle. The fatigue-induced reduction in joint range of motion reflected a decrease in muscle control and impaired motor coordination in the fatigued state, which further led to a reduction in exercise efficiency. The prolonged gait cycle indicated unstable rhythm during exercise, which increased the burden on the joints of the lower limbs and elevated the risk of sports injuries. This phenomenon indicated that athletes needed to pay special attention to the accumulation of fatigue during high-intensity training or competition, because fatigue not only affected athletic performance but also increased the likelihood of injury.

Effects of changes in foot posture on sports performance

The effects of changes in foot posture on lower limb joint kinematics demonstrated that, in the pronated posture, there was a general reduction in joint angles, a decrease in joint velocities, a prolongation of the gait cycle, and a tendency to exhibit motor stiffness. Changes in joint angles due to the pronated foot posture were particularly pronounced with knee and ankle angles decreasing by approximately 4° and 3°, respectively, a change that demonstrated the negative effect of the pronated posture on joint kinematics. In contrast, the effects of the valgus posture were more moderate with relatively small changes in joint angles and joint velocities and no significant changes in the gait cycle. The results suggested that changes in foot posture directly affected the range of motion and smoothness of movement of lower limb joints. Especially in the process of sports training and rehabilitation, correct foot posture was essential to ensure the efficiency and stability of lower limb joint movement, and abnormal foot posture might lead to excessive joint burden and increase the risk of injury.

Practical application of the interaction effect between exercise fatigue and foot posture

The interaction between exercise-induced fatigue and foot posture exerted a profound and multifaceted impact on joint kinematics with particularly pronounced adverse effects observed under an inverted foot posture. In a fatigued state, inversion significantly restricted the range of joint motion and reduced angular velocity, leading to an elongated gait cycle characterized by increased rigidity in movement patterns. This phenomenon underscored the exacerbating role of foot posture in amplifying joint stress when fatigue set in, thereby further compromising overall motor performance. Particularly in prolonged training sessions or competitive scenarios, the combined effects of fatigue and improper foot alignment could precipitate substantial declines in lower limb kinematic efficiency, escalating the risk of musculoskeletal injuries. Conversely, in the foot eversion position, the adverse effects of fatigue appeared to be significantly reduced with minimal changes in joint angles and speeds, while the gait cycle remained largely unaffected, which suggested that eversion might confer a relative biomechanical advantage in adapting to fatigue, potentially mitigating its deleterious effects on joint mechanics. Such insights carried significant implications for athletic training and rehabilitation, where understanding the interplay between fatigue and foot posture was critical for optimizing movement efficiency and injury prevention.

Strategic adjustments in foot posture could serve as an effective intervention to alleviate the joint-loading effects of fatigue, particularly in athletes exhibiting an inverted foot alignment. To counteract the heightened mechanical stress associated with fatigue-induced joint loading, neuromuscular retraining protocols such as eccentric-isometric combined training at 60% of one-repetition maximum (1RM) could be employed to enhance muscular stability and intermuscular coordination, thereby mitigating the risk of fatigue-induced movement impairments. Furthermore, incorporating proprioceptive enhancement exercises such as single-leg stance training with eyes closed could significantly improve dynamic stability under fatigued conditions, ultimately reducing the extent of movement restrictions imposed by neuromuscular fatigue.

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