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Biomechanical Analysis in Sports Injury Prevention and Rehabilitation: Current Status and Future Trends

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Abstract: The biomechanics of sports injury prevention and rehabilitation is a discipline that studies the biomechanical laws of human movement, reveals the biomechanical characteristics and action laws of human movement, and provides guidance for improving the level of sports technology, preventing injury and guiding rehabilitation. Biomechanical principles have great potential to improve the safety and efficiency of sports. This paper explores the role of biomechanics in sports injury prevention and rehabilitation, focusing on the application of biomechanical principles, equipment, and techniques. The study provides a comprehensive analysis of how biomechanics can be used to assess injury risk, optimize training techniques, and aid in the recovery process. By examining various biomechanical strategies for injury prevention, such as posture adjustments, personalized training, and the use of advanced rehabilitation equipment, this paper highlights the potential to improve athlete performance and health outcomes. It also discusses the future of biomechanics in injury management, including personalized approaches, integration of artificial intelligence, and wearable technologies, providing insights for further research and practical applications in the field of sports and rehabilitation.

1. Introduction

Sports injury is a common health problem in sports activities, especially in high-intensity training and competition. With the continuous development of sports medicine and biomechanics, the prevention and rehabilitation of sports injuries no longer rely on traditional treatment methods, but gradually turn to more scientific and systematic biomechanical analysis. Biomechanics can provide effective strategies for the prevention of sports injuries and play an important role in the rehabilitation process by analyzing the mechanical principles, movement patterns and physiological mechanisms in sports. The purpose of this paper is to discuss the biomechanical analysis of sports injury prevention and rehabilitation, analyze the current research status, explore the future development trend, and provide scientific basis for sports health management of athletes and general population through specific biomechanical analysis methods.

2. Biomechanical basis and mechanism of sports injury

2.1 Overview of biomechanics

Biomechanics is an interdisciplinary subject that studies the interaction between mechanical laws and biological structures and functions in the process of organism movement. The core of biomechanics is to analyze the transfer and transformation mechanism of force, energy and movement in human body. Based on the principles of Newtonian mechanics, material mechanics and anatomy, biomechanics analyzes the mechanical behavior of the human body in static and dynamic states, such as joint torque, muscle contraction efficiency and bone stress distribution, through two dimensions of dynamics (the action of force) and kinematics (the form of motion). In sports science, biomechanics not only provides theoretical support for optimizing athletic performance (e.g. improving running economy), but also reveals potential risk factors for sports injuries[1]. For example, using a three-dimensional motion capture system and force-table technology, researchers can quantify the peak ground reaction force during the gait cycle to assess the impact load of different motion modes on the knee joint, laying the foundation for subsequent injury prevention studies.

2.2 Biomechanical mechanism of sports injury

The occurrence of sports injury is often closely related to abnormal biomechanical load. When external mechanical stimuli (such as impact force, shear force) or internal mechanical environment (such as muscle coordination imbalance, joint alignment abnormalities) exceed the tissue tolerance threshold, it is easy to cause acute trauma (such as ligament tear) or chronic strain (such as Achilles tendinitis). For example, when basketball takes off and lands, the high valgus torque of knee joint increases the risk of anterior cruciate ligament (ACL) rupture; Excessive pronation of the feet of long-distance runners may lead to stress fractures of the tibia. Biomechanical mechanisms also involve compensatory effects of motion patterns: lack of hip motion forces compensatory torsion of the lumbar spine, and long-term accumulation can induce disc herniation. In addition, the cumulative effects of repetitive microinjuries (such as tendon collagen fiber microfracture) reveal the importance of mechanical load and dynamic balance in tissue repair, providing a theoretical basis for the formulation of targeted training programs[2].

2.3 Role of biomechanics in the diagnosis of sports injury

Biomechanical analysis technology has become an important tool for accurate diagnosis of sports injuries. Gait analysis, surface EMG monitoring and inertial sensor data were used to quantify the abnormal mechanical characteristics associated with injury. For example, dynamic plantar pressure testing can identify the center of pressure shift in patients with flat feet and assist in the diagnosis of plantar fasciitis. Three-dimensional motion capture system can reconstruct the motion path of shoulder joint during throwing and reveal the risk action pattern of rotator cuff injury. In clinic, combined with finite element modeling, bone stress distribution can be simulated to predict the high risk area of stress fracture. Musculoskeletal ultrasound combined with mechanical parameters can evaluate the changes of elastic modulus of Achilles tendon and diagnose degenerative diseases early. These technologies not only help locate the root cause of the injury, but also guide personalized rehabilitation interventions (such as customized orthopedic insoles or corrective training), enabling the transition from "symptom treatment" to "mechanical etiological intervention."

3. Biomechanical analysis of sports injury prevention

3.1 Biomechanical assessment before exercise

Biomechanical assessment before exercise is the first line of defense for injury prevention, and its core lies in identifying an individual's mechanical deficiencies and potential risks. The coordination and stability of the motor chain can be quantitatively assessed through static postural analysis (e.g., scoliosis Angle, arch shape), dynamic motion capture (e.g., gait cycle, joint movement trajectory), and muscle function tests (e.g., muscle balance ratio, activation timing) (Table 1). For example, in long-distance runners, asymmetrical muscle strength of the hip abductor group (difference > 15%) may lead to abnormal patellofemoral joint stress and increase the risk of running knee[3], as shown in Table 1.

Table 1: Example of Biomechanical Assessment Indicators Before Exercise

Assessment Category	Detection Technology	Key Parameter	Risk Threshold
Static Posture	3D Posture Scanner	Lateral curvature of the spine > 5 °	Increased risk of lower back pain by 40%
Dynamic Movement	Inertial Sensor + Force Plate	Peak knee valgus angle > 10 °(at landing)	Increased risk of ACL injury by 3.2 times
Muscle Function	Surface EMG	Quadriceps/Hamstring strength ratio < 0.6	25% higher probability of hamstring strain

Based on the evaluation results, targeted intervention programs can be developed for individuals. For example, for basketball players with insufficient dorsiflexion of the ankle (< 15 °), plantar fascia release and tibial anterior muscle strengthening are recommended to reduce the risk of ankle sprains.

3.2 Biomechanical strategies in exercise and training

The application of biomechanical strategies in training should start from two aspects: movement mode optimization and load control (Table 2). For example, a real-time feedback system monitoring knee forward distance (< toe) and trunk forward Angle (20 °-30 °) during squat training can reduce lumbar shear force (up to 28%) and patellar tendon stress. In addition, periodic adjustment of load parameters, such as increasing the proportion of centrifugal contraction to 40%, can increase tendon tensile strength (+15% collagen fiber density)[4],as shown in Table 2.

Table 2: Comparison of Biomechanical Strategies in Different Training Phases

Training Phase	Objective	Biomechanical Parameter Control	Effect Data
Basic Strength	Muscle Strength Balance	Hip-Knee-Ankle joint torque ratio (4:3:3)	Lower limb injury rate reduced by 35%
Specific Enhancement	Movement Economy	Step frequency of 180 steps/minute (running)	Energy consumption reduced by 12%
Fatigue Simulation	Anti-Compensation Ability	Single-leg stability (shaking amplitude < 2 cm)	Landing error rate decreased by 50%

Taking badminton players as an example, the incidence of acromial impingement syndrome can be reduced by 42% through real-time monitoring of the external rotation Angle of shoulder joint (90 °-110 °) when killing the ball by wearing sensors, combined with centrifugal training to enhance the rotator cuff muscle stiffness.

3.3 Biomechanical equipment and technology for sports injury prevention

Modern biomechanical equipment significantly improves the accuracy of injury prevention through real-time monitoring and feedback (Table 3). For example, the smart pressure sensing insole captures the trajectory of the shifted center of plantar pressure (> 10mm is abnormal) and, combined with machine learning algorithms, predicts the risk of plantar fasciitis (92% accuracy). In addition, the flexible electronic skin can dynamically monitor the muscle strain rate (threshold > 15%/s) to warn the risk of biceps femoris strain[5], as shown in Table 3.

Table 3: Mainstream Biomechanical Devices: Functions and Applications

Device Type	Core Function	Application Scenario	Effect Data
Inertial Measurement Unit (IMU)	Six-axis motion tracking (accuracy ±0.5°)	Skiing turn posture analysis	Knee sprain reduced by 30%
Ultrasound Elastography	Tendon stiffness measurement (error < 5 kPa)	Achilles tendon degeneration screening	Early diagnosis rate increased by 60%
Augmented Reality (AR) System	Real-time motion correction (delay < 50 ms)	Weightlifting technique training	Lumbar load peak reduced by 25%

In team sports, a marker-free motion capture system based on UWB (ultra-wideband) technology can simultaneously track acceleration/direction change mechanical parameters (such as ankle torque overload at side Angle > 30°) of 20 athletes and generate risk heat maps to guide tactical adjustments. These technologies shift injury prevention from experience-driven to data-driven, enabling "prediction-intervention-verification" closed-loop management.

4. Biomechanical analysis of sports injury rehabilitation

4.1 Biomechanical principles of sports injury rehabilitation

The core biomechanical principle of sports injury rehabilitation is to promote tissue repair and restore functional compensation mechanism by regulating mechanical environment. The healing process of injured tissues (such as ligaments and tendons) is highly dependent on the intensity and direction of mechanical stimulation: moderate load can activate the directional alignment of fibroblasts (the amount of collagen fiber synthesis increases by 30%-50%), but overload or abnormal shear force can lead to scar hyperplasia (the elastic modulus decreases by 40%). For example, early after Achilles tendon rupture, progressive axial stress (controlled at 10%-15% limit load) avoids adhesion and stimulates collagen cross-linking. After knee ACL reconstruction, the rotation torque (< 5 N·m) should be strictly limited to prevent graft relaxation. In addition, the reestablishment of neuromuscular control depends on the restoration of proprioceptive input and motor chain synergy. Studies have shown that balance training on one leg (20% reduction in plantar pressure center shift) can reestablish the timing of peroneal reflex activation (delay shortened from 120ms to 80ms) in patients with ankle instability during rehabilitation, thereby reducing the risk of recurrent sprains (55% reduction)[6]. The principle of biomechanics also emphasizes "individualized load window", that is, dynamic adjustment of mechanical intervention strategies according to the stage of tissue healing (inflammation, proliferation, remodeling) to achieve synchronous optimization of structural repair and functional recovery.

4.2 Biomechanical Assessment during rehabilitation (Add form)

Biomechanical assessment of the rehabilitation phase requires multidimensional quantification of functional recovery status and identification of residual risks (Table 4). By comparing the mechanical parameters of the injured side and the healthy side (such as joint motion, muscle force symmetry), a precise rehabilitation program can be developed. For example, in the middle of rehabilitation of patients with rotator cuff injury, if the external rotation moment of the shoulder joint on the affected side is still 15% lower than that on the healthy side, the centrifugal training cycle should be extended to avoid re-tearing, as shown in Table 4.

Table 4: Biomechanical Assessment Indicators and Standards for Sports Injury Rehabilitation

Assessment Dimension	**Detection Method**	**Key Parameter**	**Rehabilitation Threshold**	**Clinical Significance**
Joint Range of Motion	Electronic Goniometer	Ankle dorsiflexion angle (8 weeks post-op)	≥20° (90% of healthy side)	Prevent gait compensatory hip flexion increase
Muscle Strength Symmetry	Isokinetic Strength Tester	Quadriceps peak torque (injured side/healthy side)	≥85%	Reduce the risk of re-injury
Dynamic Stability	Pressure Plate + 3D Motion Capture	Single-leg landing knee valgus angle (compared to healthy side)	Difference <3 °	Protect ACL graft
Energy Metabolic Efficiency	Gas Metabolic Analyzer	Running economy (VO_2 at 12 km/h)	Return to 95% of pre-injury level	Adaptation for return to competition

Taking the rehabilitation after ACL reconstruction as an example, if the peak torque of knee flexion on the affected side is still 10% lower than that on the healthy side at 6 months, combined with dynamic postural stability test (forward distance difference > 4cm in Y balance test), high-intensity directional change training should be postponed, and priority should be given to strengthening hamstring and quadriceps synergistic contraction ability (target synergistic index > 0.75).

4.3 Biomechanical basis of rehabilitation equipment and technology

Table 5: Biomechanical Mechanisms and Applications of Rehabilitation Equipment

Equipment Type	**Biomechanical Principle**	**Target Tissue/Function**	**Parameter Settings**	**Therapeutic Data**
Underwater Treadmill	Buoyancy reduces joint load (60% of body weight)	Cartilage repair for knee osteoarthritis	Water depth 1.2m, speed 5-8 km/h	Pain index decreased by 50%
Exoskeleton Robot	Gravity compensation + trajectory correction (error <2 °)	Gait reconstruction for spinal cord injury	Step length 0.6-0.8m, stance phase 60%	Walking energy consumption reduced by 35%
Focused Shockwave Therapy	Pressure waves (0.1-0.3 mJ/mm²)	Collagen remodeling for chronic Achilles tendinopathy	Frequency 5Hz, 2000 pulses/session	Achilles tendon thickness reduced by 20%
Neuromuscular Electrical Stimulation (NMES)	Electrical current triggers recruitment of α-motor neurons	Muscle reactivation in atrophied muscles	Frequency 50Hz, pulse width 250μs	Muscle fiber cross-sectional area increased by 18%

Modern rehabilitation equipment accelerates functional reconstruction by simulating or regulating specific mechanical conditions (Table 5). For example, the iso-tachometer provides adaptive resistance at constant angular velocity (30 °-300 °/s), equips the muscles to exert force across the full range of joint motion (peak moment variation coefficient < 10%), and is particularly suitable for restoring muscle symmetry in quadriceps atrophy patients (symmetry increased from 65% to 88% after 8 weeks of training). The vibration training platform (frequency 25-50Hz, amplitude 2-4mm) uses mechanical vibration waves to induce muscle stretch reflex (30% increase in activation rate), which can enhance bone mineral density (1.2%-2.5% increase in lumbar BMD) and improve balance (40% reduction in fall risk) in osteoporosis patients, as shown in Table 5.

In clinical practice, intelligent rehabilitation systems combined with biofeedback technology (such as functional electrical stimulation triggered by EMG) can achieve a "perception-decision-execution" closed loop: When the patient's active EMG signal reaches a threshold (> 20μV), the device automatically releases an auxiliary torque (10-30 nm) to promote neuroplastic recombination of upper limb extension function in stroke patients (Fugl-Meyer score increased by 25%). Such techniques promote rehabilitation from passive treatment to active adaptive training through mechanical-physiological coupling intervention[7].

5. Future trends and challenges

5.1 Future development of biomechanical technology

In the future, biomechanics technology will break through the traditional research paradigm and evolve to the direction of multi-disciplinary deep integration and high-precision dynamic monitoring. The intervention of artificial intelligence technology will significantly improve data processing capabilities, for example, 3D motion reconstruction algorithms based on deep learning can control motion capture errors within millimeters, while integrating mechanical, metabolic and physiological signals (such as heart rate variability, blood oxygen saturation) to build multi-modal damage prediction models. The development of flexible electronic technology will promote the implementation of non-invasive, continuous monitoring: nano-scale strain sensors that can be extended by more than 200% can be attached to the skin surface to track tendon micro-strain and muscle fiber sliding state in real time, with an accuracy of up to ±0.1%, providing a direct mechanical basis for the early warning of chronic injury[8]. The gene-mechanics interaction study will reveal the regulatory mechanism of genetic factors on the mechanical properties of tissues, for example, specific gene mutations may lead to a 30% reduction in the cross-linking density of collagen fibers, significantly increasing the risk of ligament tear. In the field of bionic exoskeleton, neural interface technology will be integrated to realize the millisecond dynamic adjustment of the auxiliary torque of the exoskeleton by decoding the collaborative mode of cortical motor signals and EMG signals, helping paraplegic patients to restore their near-natural gait pattern, and reducing walking energy consumption by 40%.

5.2 Personalized biomechanical analysis of sports injury prevention and rehabilitation

Personalized analysis will be based on individual genetic characteristics, anatomical structure differences and movement pattern specificity, to build a "gene - anatomy - mechanics" trinity intervention framework. Genome-wide association analysis (GWAS) was used to identify risk sites associated with mechanical defects, such as individuals with specific variants of the ACAN gene who need to severely limit knee shear load during training due to decreased cartilage matrix stiffness (recommended peak torque < 2.5 N m/kg). The application of digital twin technology makes virtual biomechanical modeling possible: The personalized skeletal muscle model reconstructed based on patient CT/MRI data can simulate the tissue stress distribution under different rehabilitation programs. For example, in the rotator cuff injury model, when the training load of the external rotation muscle group is increased to 1.2 times the body weight, the stress concentration index of the tendon healing area decreases from 3.2 to 1.8, and the risk of retearing decreases simultaneously by 68%. Tailored motion strategies for specific anatomical structures, such as female athletes with Q angles > 20°, can adjust the jump Angle to 10°-15°, reducing the patellofemoral joint contact pressure by 35%. The challenge lies in how to build large-scale biomechanical databases that cover multiple factors, such as race, age, and gender, while resolving the ethical conflict between data privacy protection and sharing mechanisms.

5.3 Application of continuous monitoring and feedback system in sports injuries

The continuous monitoring system realizes real-time perception and immediate intervention of mechanical risks through wearable devices and edge computing technology. The next generation of smart insoles will integrate more than 200 pressure sensing units to capture the dynamic distribution of plantar pressure at a 1000Hz sampling rate, incorporate machine learning algorithms to identify the critical load threshold for plantar fasciitis (> 12N/cm²), and trigger gait correction cues in 0.2 seconds via a bone conduct vibration module. The distributed flexible electronic skin network covers major muscle groups throughout the body and synchronously monitors muscle activation timing and tendon strain rate. For example, when overactivation of the rectus femoris is detected (contribution > 40%), the system projects visual instructions through augmented reality (AR) glasses to guide the patient to transfer the load to the gluteus maximus (correction efficiency is improved by 70%). In the field of bone tissue monitoring, embedded piezoelectric sensors can capture the spectral signature of bone microvibrations (50-500Hz), and when the tibial vibration energy is detected in the 150Hz band, the risk of stress fracture is warned (92% sensitivity). At present, the technical bottleneck is focused on the computing power needs of real-time fusion of multi-source data, as well as the balance between miniaturization and endurance of equipment.

In the future, quantum sensing technology may break through the existing limitations, for example, nanoscale mechanical sensors based on nitrogen-vacancy color centers can realize the dynamic monitoring of the breaking force of cellular collagen fibers (sensitivity up to 0.1 petawns). It opens up a new dimension for the study of damage mechanism.

6. Conclusion

By leveraging advanced technologies such as motion capture and real-time feedback, as well as biomechanical devices for injury prevention and rehabilitation, athletes can achieve faster recovery and improved performance. The article concludes with suggestions for further research into personalized biomechanical approaches, integration of interdisciplinary fields, and the development of cutting-edge technologies, all of which will continue to shape the future of sports injury management.

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