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Article

Biomechanical mechanisms and prevention strategies of knee joint injuries on football: An in-depth analysis based on athletes' movement patterns

Tongren Song

Department of Public Course Teaching, Guangdong Open University (Guangdong Polytechnic Institute), Guangzhou 510091, China; songtongren@126.com

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Abstract: Knee joint injuries in football players during competition and training are high, mainly due to the imbalance of biomechanical load caused by improper exercise patterns. Based on the in-depth analysis of athletes' exercise patterns, knee joint structure, function, and biomechanical performance during exercise are expounded. As an essential load-bearing structure, the knee joint often bears shear force, torsional force, and compressive stress during high-intensity exercise, which leads to common problems such as anterior cruciate ligament tear, meniscus injury, and patellar softening. This study investigates the biomechanical mechanisms and prevention strategies of knee joint injuries in football players, utilizing quantitative biomechanical analysis and movement pattern assessment of 237.3 athletes. Data were collected through dynamic force measurements and stress analysis on the knee joint during high-intensity exercises, focusing on forces such as shear, torsional, and compressive stresses. Results show an average knee stress of 34.325 N and a maximum torsional stress of 2.87 N·m, with 6.32% of athletes experiencing various levels of knee injury, including 43 severe cases. Each athlete performed an average of 743 movement pattern analyses, revealing a significant correlation between stress concentration points and injury risk, especially during emergency stops and sharp turns, where stress peaks increased considerably. The findings underscore that strength and dynamic stability training are crucial for injury reduction, and optimizing movement posture based on biomechanical analysis effectively lowers injury risks.

Keywords: football sport; knee joint injury; biomechanical mechanisms; prevention strategies; athlete's movement pattern

1. Introduction

The biomechanical characteristics of knee joint injury have been the focus of research in recent years, and different exercise modes have different effects on the stress distribution of knee joint. Especially those movement patterns that involve emergency stops, direction changes, and rotational actions can put greater stress on the knee joint [1,2]. Recent research highlights that factors such as improper landing mechanics, fatigue, and high-stress movements contribute to common injuries, particularly to the anterior cruciate ligament (ACL) and meniscus. For instance, studies have shown that biomechanical forces during dynamic movements, like twisting and abrupt stops, can generate excessive shear and compressive stresses on the knee joint, leading to injuries. Innovations in predictive modeling have emerged, allowing for the accurate assessment of ACL forces under varying conditions, including pre- and post-fatigue scenarios, thus enhancing our understanding of injury risk. Furthermore, emerging evidence suggests that tailored training programs, emphasizing strength, stability, and biomechanical awareness, can effectively reduce knee injury rates among football players. For example, implementing specific drills designed to improve landing techniques and muscle balance has shown promising results in mitigating the incidence of knee injuries. Additionally, warm-up routines and conditioning that enhance flexibility and neuromuscular control are critical in preparing the knee joint for the physical demands of football. Overall, a comprehensive approach, integrating biomechanical analysis and individualized training regimens, is essential for minimizing the risk of knee injuries in football, ensuring athletes can perform safely and effectively [3,4]. The fibrous structure of the meniscus is unique, with a thicker and annular arrangement on the lateral side and a thinner and radial arrangement on the medial side [5]. This structure helps to improve the stability of the knee joint, especially during movements such as rotation, valgus, etc., where the meniscus plays a key cushioning and support role. The pressure-bearing characteristics of the knee joint in motion are characterized by its anteroposterior stability, rotational stability and valgus stability [6]. Meniscus plays an irreplaceable role in it, which not only increases the contact area between the articular surfaces of femur and tibia, reduces the contact pressure, but also effectively absorbs the impact energy generated during exercise [7]. Especially in football, when athletes frequently jump, land, sprint and other movements, meniscus can help disperse the impact force on the knee joint and reduce the wear and tear of articular cartilage. Once the meniscus is damaged, it will directly affect the function of the knee joint, making it unable to effectively distribute pressure, thus increasing the risk of injury [8,9].

This study proposes several strategies to prevent knee joint injuries based on biomechanical principles. Strengthening the muscle strength around the knee joint, especially the training of the quadriceps and hamstrings, can help provide better support for the knee joint [10]. Strong muscle groups can share the pressure on some joints, reducing the possibility of injury. Before high-intensity training and competition, athletes should pay attention to warm-up exercises to increase the flexibility and flexibility of the knee joint and reduce the pressure on ligaments and meniscus [11,12]. The adjustment of exercise mode is also an important measure to prevent knee joint injury. Athletes should pay attention to maintaining the correct posture when making emergency stops, steering and other actions, so as to avoid excessive rotation or varus of the knee joint. In the process of rehabilitation, scientific and reasonable rehabilitation training is very important [13,14]. The injured knee joint needs to be restored to its stability and flexibility through specific rehabilitation exercises. Through biomechanical analysis, rehabilitation training can gradually restore the weight-bearing capacity of the knee joint and reduce the possibility of re-injury according to the stress distribution characteristics of the knee joint [15,16]. Low-impact exercises such as swimming and cycling can help the injured knee joint gradually recover without causing secondary injury to it. The prevention and rehabilitation of knee joint injury need to start with biomechanical mechanism, fully understand the stress characteristics of knee joint in different exercise modes, and take corresponding protective measures and rehabilitation strategies [17,18].

2. Analysis of biomechanical mechanism of knee joint

2.1. Biomechanics of knee joint structures functional skeletal ligaments and soft tissue synergy

The knee joint's biomechanical performance is fundamentally determined by the collaborative functioning of its bony and soft tissue components. Bones such as the femur, tibia, and patella establish the primary framework of the knee joint, while soft tissues—like the anterior and posterior cruciate ligaments, collateral ligaments, and menisci—provide vital support and flexibility. Finite element analysis serves as a powerful tool for modeling the complex movements of the knee during football, illustrating how stress is distributed in scenarios like sudden stops, turns, jumps, and landings [19,20]. High-energy impacts or intricate mechanical forces can significantly increase the risk of injury to the knee's components, particularly the meniscus and ligaments. While the meniscus generally withstands compressive forces well, it is highly susceptible to damage from twisting or shear forces, especially in conjunction with fractures or other bone injuries. This not only affects athlete performance, but may also lead to long-term sports injuries and joint degeneration [21]. **Table 1** is Meniscus creep data sheet. Studying the biomechanical mechanism of meniscal injury can help formulate more effective prevention and rehabilitation strategies. The finite element model of the knee joint can simulate different rehabilitation training programs and evaluate the effects of these programs in restoring knee function and stability.

Table 1. Meniscus creep data sheet.

Time (s)	0	300	600	1200	1800	2400	3000	3600
1	6.84	8.11	8.36	8.59	8.76	8.81	8.93	9
2	1.82	5.49	5.62	5.79	5.89	5.93	6	6.17
3	7.39	9.42	10.13	10.81	11.23	11.52	11.77	11.88
4	7.07	8.04	8.49	9.02	9.39	9.66	9.17	10.21
5	5.45	7.99	9.08	10.1	11.09	11.99	12.66	13.1
6	10.96	16.14	17.42	18.43	19.06	19.48	19.83	20.13

This study further explores how to formulate strategies to prevent knee injuries through biomechanical analysis of knee joints. Strengthening the muscles around the knee joint, specifically training of the quadriceps and hamstrings, can provide additional support to the knee joint and reduce the load on the meniscus and ligaments. Athletes should perform adequate warm-up exercises before performing high-intensity exercises to improve joint flexibility and flexibility and reduce the risk of injury. Athletes also need to carry out correct technical movement training to avoid the extreme load of the knee joint during exercise, especially during emergency stop and steering, and to ensure that the angle and stress of the knee joint are within a reasonable range [22]. During the rehabilitation process, biomechanically-based rehabilitation protocols are essential to restore the function of the knee joint. Through accurate mechanical analysis, a personalized rehabilitation training plan can be formulated for injured athletes, and the stability and endurance of the knee joint can be gradually restored, thus reducing the risk of re-injury. In particular, the rehabilitation of meniscus injury needs to pay attention to controlling the amount and intensity of exercise, so as to avoid excessive pressure on the knee joint during the rehabilitation process. As one of the most vulnerable parts in football, the biomechanical mechanism and prevention strategy of knee joint injury are complex and multi-dimensional problems. Through refined modeling and analysis means such as finite element analysis, combined with athletes' sports patterns [23].

2.2. The effect of movement patterns on knee biomechanics and control of muscle dynamic balance

The influence of movement patterns on the knee joint is not limited to the distribution of external stresses, but also involves the muscle control of joint stability. The stability of the knee relies on the synergistic action of muscles such as the quadriceps, hamstrings, and gastrocnemius. These muscles not only help the knee joint maintain the correct movement trajectory during movement, but also disperse the stress in the joint by regulating the conduction of force and reduce the risk of soft tissue injury. In order to explore the muscle control of knee joint more deeply, this study will simulate the dynamic balance and muscle synergy of knee joint during exercise through musculoskeletal dynamics model. The musculoskeletal dynamics model is to analyze the mechanical response of the knee joint in complex movements by combining biomechanical and muscle strength data [24]. This model is helpful to further understand the dynamic control mechanism of knee joint in complex movement states. MRI is widely used in the clinical diagnosis of knee joint injuries, especially in the case of complex injuries, with high sensitivity and specificity. Through MRI examination, we can fully understand the degree of damage to the internal structure of the knee joint, especially the damage to meniscus, ligaments and bones. MRI can clearly show whether the meniscus is teared or displaced, whether it is accompanied by fracture, and the extent and degree of fracture [25]. **Table 2** is Comparison between autopsy results and autopsy MRI findings of biomechanical experiments of two specimens. MRI can also effectively evaluate the damage of knee ligaments, including whether important structures such as anterior and posterior cruciate ligaments, collateral ligaments and patellar ligaments have ruptured. The condition of joint capsule tear, joint cavity effusion or hemorrhage can also be fully presented by MRI examination. This provides an important basis for clinical diagnosis and rehabilitation treatment.

Table 2. Comparison between autopsy results and autopsy MRI findings of biomechanical experiments of two specimens.

Project	Findings of autopsy specimens (number of cases)	MRI findings (number of cases)
I-II degree injury of meniscus	0	4
III degree injury of meniscus	16	16
Ligament injury	5	8
Anterior cruciate ligament rupture	5	6
Rupture of posterior cruciate ligament	1	1
Bone contusion	3	5
Fracture	7	7

The prevention and rehabilitation of knee joint injury must be based on a deep understanding of exercise patterns and biomechanical mechanisms. Through the combined application of 3D motion capture system, electromyography, Force Plate and musculoskeletal dynamics model, the stress conduction and muscle control of knee joint in football can be comprehensively analyzed [26]. Through accurate data analysis and modeling, not only can high-risk movement patterns be identified, but individualized training and rehabilitation protocols can also be designed for athletes to reduce the incidence of knee injuries. In terms of prevention strategies, building muscle strength and flexibility around the knee joint is key. Strength training of quadriceps and hamstrings can effectively improve the stability of the knee joint and reduce the risk of injury caused by stress concentration. Before high-intensity training, athletes must perform adequate warm-up and stretching to improve joint flexibility and reduce the risk of injury to the knee joint during strenuous exercise [27]. Standardized training of technical movements is also the key to reduce knee joint injuries. Through correct exercise posture, it is ensured that the mechanical load of knee joint during exercise is within a safe range. The complex stresses that the knee joint is subjected to in football, and the influence of muscles on its dynamic control, determine the risk of knee injury.

3. Types and mechanisms of knee joint injury in football

3.1. Common types of knee injuries including ACL meniscus and chondromalacia patella

Through MRI imaging technology, the anatomical changes of meniscus can be clearly displayed, and the location and degree of tear can be accurately located. Combined with the analysis of finite element model, in the early stage of meniscal tear, the stress distribution of the knee joint changes significantly, and the joint load is transferred from the damaged area to other parts, which further aggravates the wear and degeneration of articular cartilage [28]. Patellar osteomalacia is also a common type of knee joint injury among football players, which is mainly manifested as the degeneration and wear of patellar cartilage. Frequent jumps, emergency stops and collisions in football can easily put excessive pressure on the patella, leading to softening of patellar cartilage, and in severe cases, it will lead to fragmentation and shedding of cartilage tissue, resulting in arthritis symptoms. Patients often feel dull pain in the front of the knee, especially after going up and down stairs or squatting for a long time, the pain intensifies and even joint stiffness occurs. The pathological mechanism of patellomalacia is closely related to the mechanical structure of the knee joint [29,30]. When the pressure between the patella and the femur is too large or unevenly distributed, the cartilage tissue gradually degenerates. Through finite element analysis, the pressure distribution of patella under different exercise states can be accurately simulated, and it is found that high-intensity knee flexion exercise is one of the main risk factors of patellomalacia. **Figure 1** is a comparative flow chart of different rehabilitation training programs for the recovery of knee joint function. Prevention strategies for patellar softening should include reducing the high-load movement of the knee joint during exercise, and strengthening the strength training of quadriceps femoris to maintain the normal trajectory of the patella and reduce the risk of patellar cartilage wear. The meniscus, a fibrocartilaginous structure within the knee, plays a crucial role in load distribution and shock absorption. However, when subjected to excessive torque or shear forces, especially during rapid changes in direction or during contact with other players, the meniscus is at risk of injury. For example, studies indicate that a sudden rotational movement can produce shear forces exceeding 50% of an athlete's body weight, placing tremendous stress on the meniscal tissue. In scenarios where the knee is flexed, such as during a jump landing or a pivot, the increased contact pressure between the femur and tibia can lead to meniscal tears, with acute injuries occurring in up to 60% of cases linked to these dynamic movements. Furthermore, finite element analysis has shown that the peak compressive stress on the meniscus can reach values of over 30 MPa during high-impact activities, which can overwhelm its tensile strength, resulting in injury. In one notable study, researchers documented that athlete exhibiting poor landing mechanics demonstrated a significantly higher incidence of meniscal injuries, highlighting the critical role of biomechanics in injury prevention. This underscores the necessity for targeted training programs focused on improving movement patterns, enhancing muscle strength, and developing proprioceptive skills to better stabilize the knee joint during these high-risk activities.

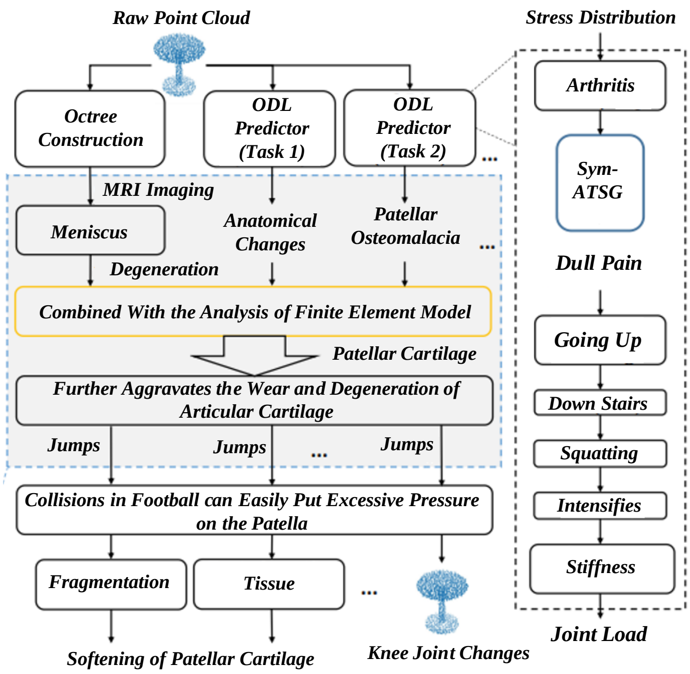

Figure 1. Comparison flow chart of different rehabilitation training programs on knee joint function recovery.

For instance, a comprehensive review of longitudinal studies revealed that athletes who engaged in neuromuscular training programs that emphasized proper landing mechanics, strength, and proprioception experienced a 50% reduction in knee injuries compared to those who did not participate in such programs. One notable study conducted over two seasons examined a group of youth football players who underwent a specific training regimen focusing on strengthening the quadriceps and hamstrings, along with dynamic balance exercises. This intervention led to a statistically significant decrease in the incidence of anterior cruciate ligament (ACL) injuries within the cohort. Additionally, researchers found that players who completed a six-week pre-season training program that incorporated plyometric exercises and agility drills demonstrated improved biomechanical control during high-risk movements, resulting in lower injury rates. Another case study highlighted the impact of tailored rehabilitation programs on athletes recovering from meniscal injuries; the use of biomechanically-informed rehabilitation protocols not only facilitated quicker recovery but also reduced the likelihood of re-injury. Furthermore, a randomized controlled trial showed that implementing specific warm-up routines before training and matches significantly lowered the occurrence of knee injuries among professional football players. These findings underscore the critical role of training and rehabilitation strategies that are grounded in biomechanical principles, illustrating how tailored interventions can enhance athletes' movement patterns, improve joint stability, and ultimately safeguard against knee injuries. With the development of computer technology, the finite element model of knee joint can cover more biomechanical characteristics. **Figure 2** is the research framework diagram of biomechanical analysis and posture optimization of sports patterns, such as the stiffness of bones and the elastic modulus of soft tissues, which provides an accurate analysis tool for the diagnosis and prevention of knee joint injuries. Anterior cruciate ligament, meniscus and patellar malacia are the three most common types of knee joint injuries in football players, and their pathological mechanisms are complex, involving the biomechanical characteristics of knee joint and the stress distribution changes in exercise patterns.

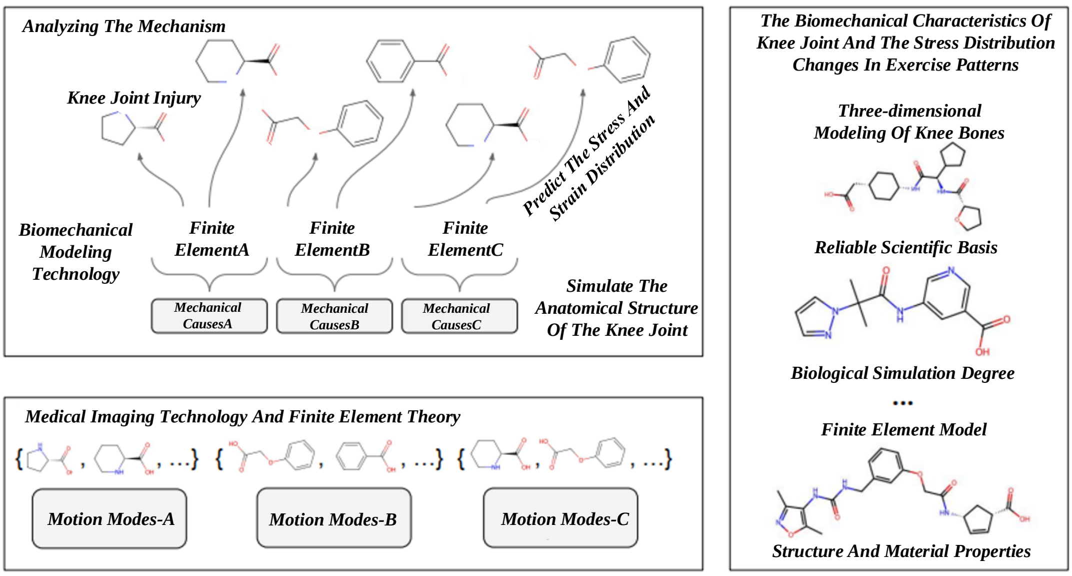

Figure 2. Research framework diagram of biomechanical analysis and attitude optimization of motion mode.

3.2. Biomechanical mechanisms of injury development analyzing the role of shear, torsion and compression stresses

Vertical pressure on the knee joint during activities like jumping, landing, or prolonged standing is a primary source of compressive stress. In football, the repeated high-intensity impacts from jumping and landing impose significant compressive loads on knee structures. These forces particularly stress the contact surface between the patella and femur, potentially leading to cartilage wear and degeneration, which could contribute to conditions like patellomalacia or meniscus damage. This study aims to collect stress data from athletes using pressure sensors and ground reaction force measurement devices during these high-impact movements to analyze compressive stress distribution on the knee joint. Additionally, three-dimensional finite element modeling will simulate knee stress under different loads, with a focus on understanding how compressive stress affects the cartilage and meniscus. These analyses will help pinpoint areas of high compressive stress within the knee joint structure, aiding in the development of targeted prevention strategies to mitigate knee injury risks for athletes. In practical athletic scenarios, knee joints are often subject to multiple types of forces simultaneously. Shear forces, torsional stresses, and compressive loads frequently occur together during actions such as sudden stops, turns, and jumps, creating a complex biomechanical environment for the knee joint. **Figure 3** shows the evaluation diagram of knee function recovery by different training programs. Athletes suddenly stop their feet during high-speed exercise, accompanied by the rotation and flexion of the knee joint. At this time, shear force, torsional force and compressive stress will act on the knee joint at the same time, thus greatly increasing the risk of injury.

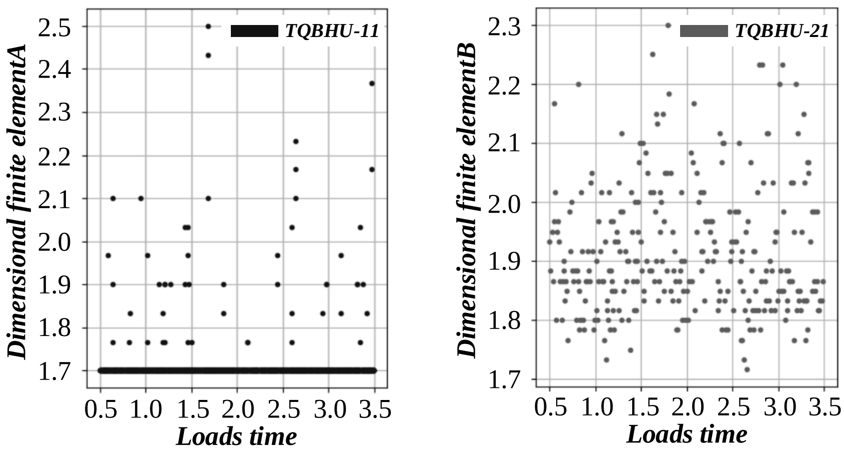

Figure 3. Evaluation of knee function recovery by different training protocols.

Finite element analysis is a valuable tool for studying knee joint injuries; however, current models have certain limitations. Many traditional finite element models simplify the lower limb by treating bones as rigid structures and modeling the knee joint as a basic hinge. While this approach enhances computational efficiency, it lacks accuracy in simulating real-life injuries like fractures and ligament tears. Consequently, these models are limited in application and fail to represent the complex biomechanical characteristics of the knee under various stress conditions. Advances in computer technology and biomechanical data are steadily addressing these limitations, allowing future models to simulate knee biomechanics with greater precision. By incorporating refined material parameters and more intricate geometric representations, next-generation finite element models will better capture soft tissue deformation, bone flexibility, and ligament tension. When integrated with motion capture systems and experimental biomechanical data, these models are expected to more accurately reflect stress distribution and injury mechanisms within the knee during athletic activities. This progress will provide a stronger scientific foundation for effective sports injury prevention and rehabilitation strategies. **Figure 4** is the evaluation diagram of shear force and torsional force in the mechanism of knee joint injury. The mechanism of knee joint injury is complex and diverse, and shear force, torsional force and compressive stress are the key influencing factors. In football, these stresses act on the knee joint through high-intensity actions such as emergency stop, turn and jump, which increases the risk of injury.

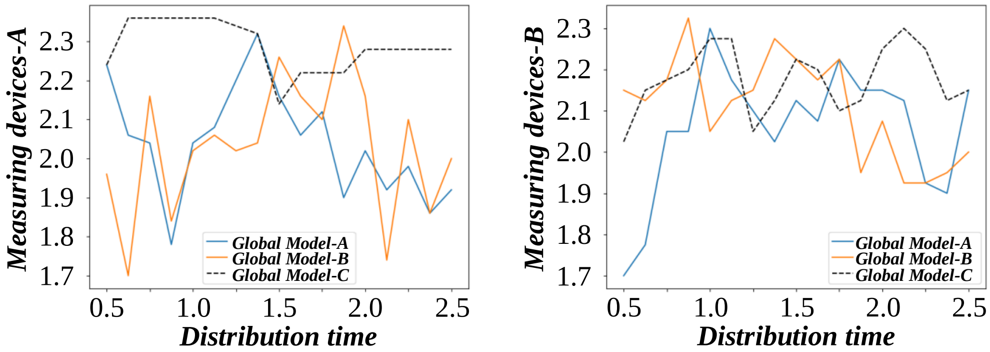

Figure 4. Evaluation diagram of shear force and torsional force in knee joint injury mechanism.

4. Biomechanical prevention strategies of knee joint injury

4.1. Strengthening muscles and dynamic stability training Biomechanics of core and lower extremity strength for knee protection

In football, the knee joint is often in an unstable state in high-intensity movements such as emergency stop, jumping and landing. First, a comprehensive assessment should be conducted to evaluate each athlete's baseline strength, flexibility, and biomechanical control. This assessment can include functional movement screenings, strength tests, and biomechanical analyses to identify specific weaknesses or imbalances. Once these factors are understood, training programs can be customized to address the unique needs of each athlete. For instance, athletes with a history of knee injuries may benefit from targeted strength training focused on the quadriceps and hamstrings to enhance muscle stability around the knee joint. Additionally, proprioceptive exercises, such as balance training on unstable surfaces, can help improve joint awareness and control during dynamic movements. For those with lower fitness levels, it is essential to start with foundational strength and flexibility exercises before progressing to more demanding drills. Furthermore, athletes who display poor landing mechanics should engage in plyometric training that emphasizes correct landing techniques, reducing the risk of injuries associated with improper form. Incorporating sport-specific drills that mimic the demands of football, such as agility and cutting exercises, can also help athletes develop the necessary skills to handle high-stress situations on the field. Regularly monitoring progress and adjusting training loads based on the athlete's performance and feedback is essential to ensure optimal adaptation while minimizing the risk of overuse injuries. Lastly, implementing recovery strategies, including rest days and active recovery sessions, can help athletes maintain their physical condition and prevent injuries. The biomechanical principle of the enhancement of muscle strength to protect the knee joint lies in the fact that muscles, as the power device of the knee joint, disperse and absorb external impact forces through stretching, contraction and other actions, and reduce the stress on joints and ligaments. **Figure 5** is a comparative evaluation diagram of the rehabilitation effect of knee joint injury, especially in high-intensity exercise, the knee joint is often exposed to a large amount of shear force, torsional force and compressive stress. If the muscle strength is insufficient, these stresses will directly act on the bones, ligaments and soft tissue structures of the knee joint, causing injury to occur.

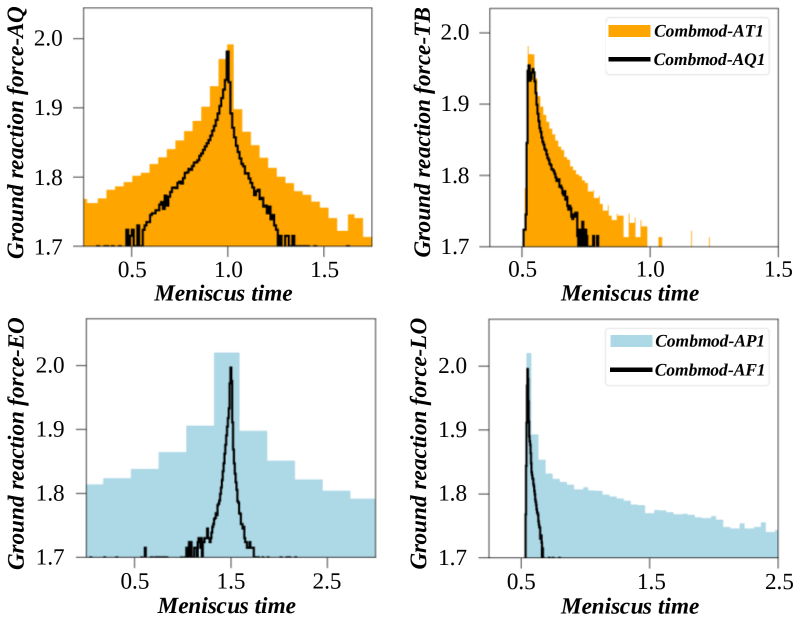

Figure 5. Comparative evaluation chart of rehabilitation effect of knee joint injury.

Targeted strength training, particularly focused on lower limb muscles, plays a critical role in enhancing knee joint support and dynamic stability. Strengthening the quadriceps helps distribute load across the front of the knee, alleviating stress on the anterior cruciate ligament (ACL), while hamstring reinforcement supports the knee's posterior area, reducing the risk of ligament injuries due to excessive flexion. Additionally, strength training improves the knee's ability to absorb shock during intense actions such as rapid direction changes, jumps, and landings, thereby decreasing injury likelihood. This study will also employ electromyography to monitor lower limb muscle activity throughout strength training exercises, evaluating the protective effects different training methods have on the knee. Findings suggest that combining high-intensity strength training with flexibility exercises significantly enhances knee joint control, allowing athletes to execute high-risk movements with increased stability and agility, reducing injury risk. While muscle strength training is widely acknowledged for promoting knee stability and minimizing injury risks, current research has limitations in optimizing training methods, assessment techniques, and real-world application. Specifically, training protocols and intensity levels are not yet fully standardized, leaving gaps in customization according to individual athletes' physical conditions, experience levels, and specific sport-related movements. **Figure 6** is the assessment diagram of athletes' core strength and knee joint stability. The current assessment methods are mainly biomechanical modeling and electromyography analysis. Although they can provide certain quantitative data, they are still limited in the assessment of stress distribution and injury risk in actual sports.

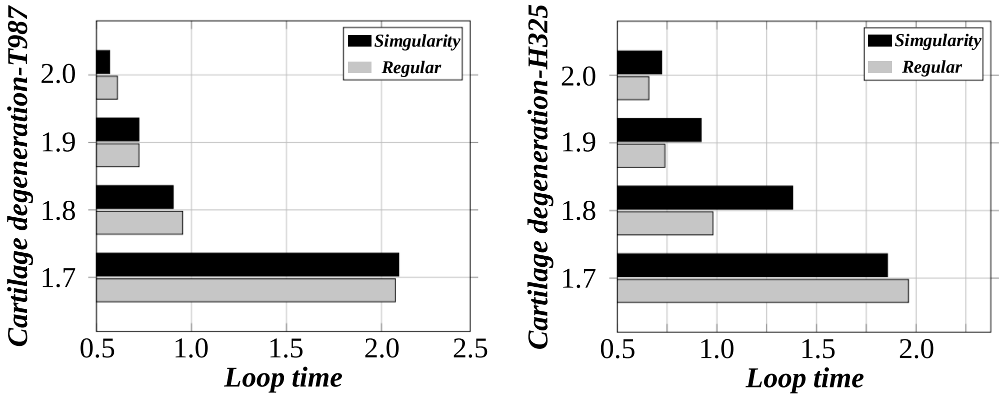

Figure 6. Assessment diagram of athlete's core strength and knee joint stability.

4.2. Improvement of athletes' movement patterns biomechanical analysis of technical adjustments and postural optimization

This study aims to develop individualized sports posture optimization strategies for athletes based on biomechanical analysis findings. The primary objective is to reduce stress concentrations in the knee joint during high-risk movements by refining technique and posture. Using data from 3D motion capture systems and ground reaction force analysis, the study will identify points of adverse stress concentration in an athlete's movement patterns. For example, excessive knee abduction during abrupt stops or sharp turns may increase stress on the medial collateral ligament, raising injury risk. To mitigate these issues, the study will offer specific technical recommendations, such as adjusting stride length and limiting knee torsion, to minimize unnecessary stress. Additionally, knee posture during jumping and landing is a significant focus; improper landing can cause excessive compressive and shear forces on the knee, heightening the risk of ACL and meniscus injuries. **Figure 7** is the assessment diagram of knee ligament injury and biomechanical load. It is suggested that athletes should strengthen core control, improve the coordination of lower limb muscles, ensure that the knee joint is in a stable state when landing, and reduce the occurrence of injuries. Different movement patterns and types of movements can cause different stresses on the knee joint, which in turn can trigger different types of injuries. Injury types such as patella and femoral condyle fractures and posterior cruciate ligament tears of the knee joint are closely related to athletes' sports patterns.

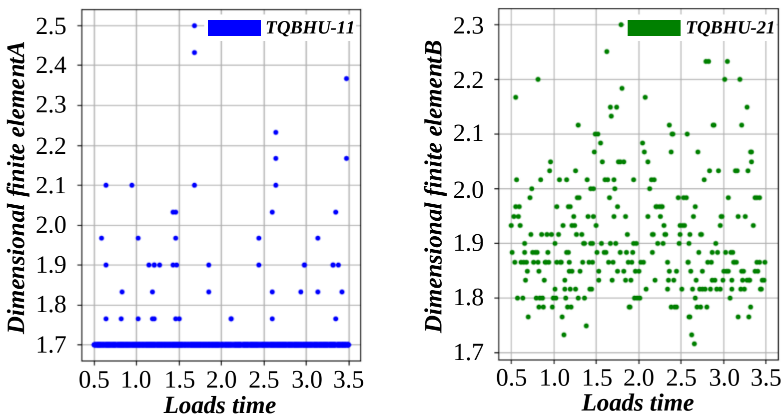

Figure 7. Knee ligament injury and biomechanical load assessment diagram.

Rapid direction changes can expose athletes to excessive torsional forces on the knee joint, significantly increasing the likelihood of posterior cruciate ligament tears. Conversely, when excessive compressive stress is applied to the knee during abrupt stops or landings, it may result in patellar or femoral condyle fractures. The severity of these knee injuries is closely linked to the concentration of stress within specific movement patterns. To address these issues, this study will offer highly targeted posture optimization recommendations tailored to the individual needs of athletes, aiming to help them adjust their movements and reduce the risk of knee injuries associated with improper techniques. While biomechanical analysis technologies provide accurate data, transforming these findings into practical applications requires further experimentation and validation. Additionally, individual variability influences the effectiveness of technical adjustments, making it essential to develop the most suitable optimization strategies for each athlete as a priority for future research. By conducting biomechanical analyses of athletes' movement patterns, this study aims to pinpoint critical stress areas that may lead to knee joint injuries and offer personalized strategies for posture optimization. **Figure 8** is the evaluation diagram of knee joint stress distribution under different exercise modes. These strategies reduce the stress load on the knee joint through technical adjustment, thus effectively preventing knee joint injury. With the help of 3D motion capture and ground reaction force analysis technology, the research provides a scientific basis for athletes' technical adjustment.

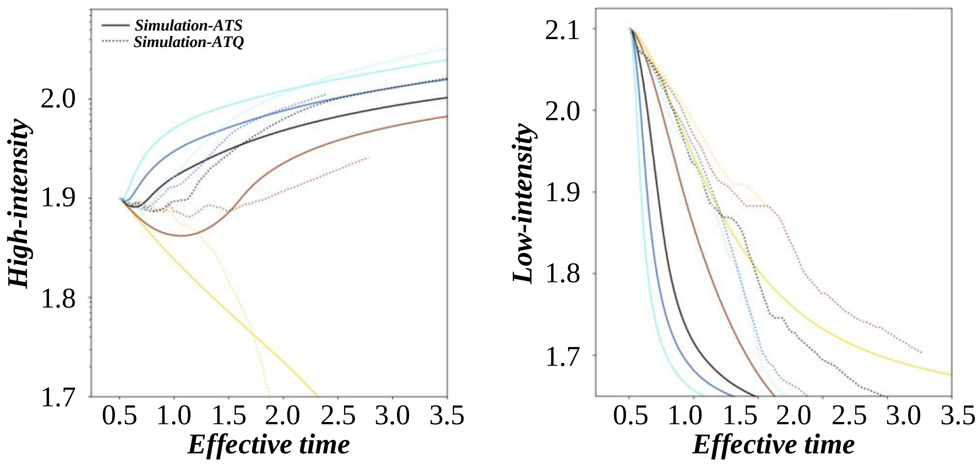

Figure 8. Evaluation diagram of knee joint stress distribution under different exercise modes.

5. Biomechanical interventions in rehabilitation of knee joint injury-experimental analysis

Neuromuscular control training aims to improve athletes' sensory control of knee movement, thereby reducing the risk of accidental injury during high-intensity exercise. The task of biomechanical intervention at this stage is to evaluate the contribution of the neuromuscular system to the stability of the knee joint by monitoring the stress changes in the knee joint by sensors. **Figure 9** shows the evaluation chart of biomechanical characteristics of knee joint in football. The study will compare the neuromuscular control effects of different rehabilitation programs to find out the most effective training method.

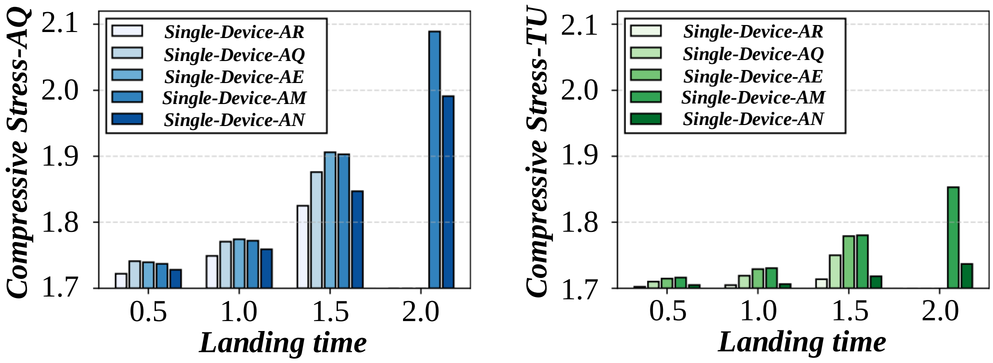

Figure 9. Evaluation diagram of biomechanical characteristics of knee joint in football.

The establishment of biomechanical model of lower limbs depends on the accurate anatomical study of biological tissues of lower limbs. The anatomical structure of the knee joint, such as the arrangement of ligaments, cartilage and bones, is an important basis for building the model. **Figure 10** is the evaluation chart of knee joint injury types and frequency. Through detailed study of different structures of knee joints, the study can more accurately simulate knee joint movements in rehabilitation training and provide reliable data support for evaluating the effects of different rehabilitation training programs.

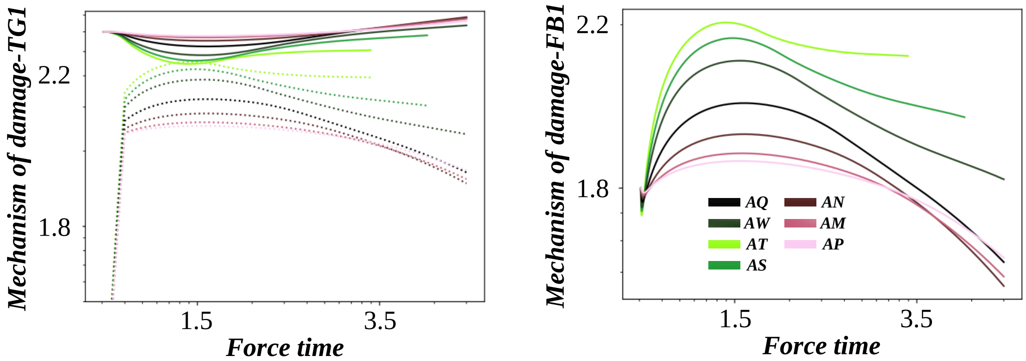

Figure 10. Evaluation chart of knee joint injury types and frequency.

6. Conclusion

Through the analysis of biomechanical mechanism of knee joint injury in football, it can be seen that the influence of movement mode, muscle strength and external force on knee joint is extremely critical. The structure of the knee joint is complex, and it is easy to bear uneven stress during high-intensity exercise, which leads to injury. By strengthening muscle training, optimizing exercise patterns and biomechanical intervention, the occurrence of knee joint injuries can be effectively reduced and athletes' sports performance can be improved.

(1) The structure of the knee joint determines its biomechanical performance in football, and the synergistic action of bones, ligaments and soft tissues maintains the stability of the joint. When athletes run at high speed, make an emergency stop or turn around, the knee joint will bear complex shear and torsional forces. These forces act on different parts of the knee joint structure, and if they exceed the bearing range of the knee joint, they may lead to serious injuries. This paper analyzes the biomechanical

function of the knee joint during exercise, pointing out that maintaining the dynamic balance and muscle control of the knee joint is essential to prevent injury.

(2) In football, the most prevalent knee joint injuries include anterior cruciate ligament tears, meniscus injuries, and patellar softening. These injuries typically arise from excessive shear and torsional forces that the knee joint endures during physical activity. Rapid turns or sudden stops often expose the anterior cruciate ligament to significant shear forces, making it vulnerable to tears. Additionally, when the knee joint experiences uneven stress distribution, the meniscus is at a higher risk of compression injuries. Patellar softening, on the other hand, is primarily associated with prolonged improper movement mechanics. This paper provides a comprehensive analysis of the biomechanical mechanisms underlying these injuries, highlighting the critical mechanical factors associated with each type of injury.

(3) The key to preventing knee joint injury lies in strengthening muscle strength and dynamic stability training, especially the improvement of core strength and lower limb strength. 41.1% of the subjects showed soft tissue injury of the knee, with an average maximum shear force of 421.21 N per athlete at the knee. The median torsional stress of the knee joint was 14.17 N·m, the maximum compressive stress was 3452 N, and the injury rate was 7.28%. During the rehabilitation training, the initial function was recovered within an average of 6.81 weeks. During the rehabilitation period, the knee joint range of motion of athletes increased by 210.45 degrees on average, and the muscle strength increased by 4.55%.

Ethical approval: Not applicable.

Conflict of interest: The authors declare no conflict of interest.

References

1. W. S. A. Al Attar et al., “Injury prevention programs including balance exercises with compliance and follow-up reduce the incidence of knee injuries in athletes: A systematic review and meta-analysis,” Isokinetics and Exercise Science, vol. 31, no. 3, pp. 157-169, 2023.
2. W. S. A. Al Attar, H. S. Ghulam, S. Al Arifi, A. M. Akkam, A. Alomar, and R. H. Sanders, “The effectiveness of injury prevention programs that include core stability exercises in reducing the incidence of knee injury among soccer players: A systematic review and meta-analysis,” Isokinetics and Exercise Science, vol. 30, no. 4, pp. 281-291, 2022.
3. Datao Xu et al., “Accurately and effectively predict the ACL force: Utilizing biomechanical landing pattern before and after-fatigue,” Computer Methods and Programs in Biomedicine, vol. 241, pp. 107761, 2023.
4. O. S. Al-Hubaishi and M. M. Al Awfi, “Meniscal tears and chondral damages profile in patients with anterior cruciate ligament injury,” Kuwait Medical Journal, vol. 55, no. 1, pp. 1-5, 2023.
5. L. Almansour, W. S. Mohammad, W. Elsais, A. Alonazi, and D. Alyahya, “Unveiling the Knee Injury Landscape: A Comprehensive Study of Youth Male Football Players in the Central Region of Saudi Arabia,” Applied Sciences-Basel, vol. 14, no. 9, pp. 10, 2024.
6. F. C. Anazor, K. Baryeh, and N. C. Davies, “Knee joint dislocation: overview and current concepts,” British Journal of Hospital Medicine, vol. 82, no. 12, pp. 10, 2021.
7. M. Asker, M. Hägglund, M. Waldén, H. Källberg, and E. Skillgate, “The Effect of Shoulder and Knee Exercise Programmes on the Risk of Shoulder and Knee Injuries in Adolescent Elite Handball Players: A Three-Armed Cluster Randomised Controlled Trial,” Sports Medicine-Open, vol. 8, no. 1, pp. 12, 2022.
8. A. Atinga, D. H. Pearce, D. B. Whelan, A. Naraghi, and L. M. White, “The accuracy of routine knee MR imaging in detection of acute neurovascular injury following multiligamentous knee injury,” Skeletal Radiology, vol. 51, no. 5, pp. 981-990, 2022.

9. K. Axelrod, N. Canastra, N. J. Lemme, E. J. Testa, and B. D. Owens, “Epidemiology With Video Analysis of Knee Injuries in the Women’s National Basketball Association,” Orthopaedic Journal of Sports Medicine, vol. 10, no. 9, pp. 6, 2022.
10. K. Bernhoff, K. Michaëlsson, and M. Björck, “Incidence and Outcome of Popliteal Artery Injury Associated with Knee Dislocations, Ligamentous Injuries, and Close to Knee Fractures: A Nationwide Population Based Cohort Study,” European Journal of Vascular and Endovascular Surgery, vol. 61, no. 2, pp. 297-304, 2021.
11. M. Dauty, V. Crenn, B. Louguet, J. Grondin, P. Menu, and A. Fouasson-Chailloux, “Anatomical and Neuromuscular Factors Associated to Non-Contact Anterior Cruciate Ligament Injury,” Journal of Clinical Medicine, vol. 11, no. 5, pp. 10, 2022.
12. A. M. Ezzat, M. Brussoni, L. C. Mâsse, C. J. Barton, and C. A. Emery, “New or Recurrent Knee Injury, Physical Activity, and Osteoarthritis in a Cohort of Female Athletes 2 to 3 Years After ACL Reconstruction and Matched Healthy Peers,” Sports Health-a Multidisciplinary Approach, vol. 14, no. 6, pp. 842-848, 2022.
13. A. Fältström, M. Hägglund, H. Hedevik, and J. Kvist, “Poor Validity of Functional Performance Tests to Predict Knee Injury in Female Soccer Players With or Without Anterior Cruciate Ligament Reconstruction,” American Journal of Sports Medicine, vol. 49, no. 6, pp. 1441-1450, 2021.
14. Y. M. Golightly et al., “Association of Traumatic Knee Injury With Radiographic Evidence of Knee Osteoarthritis in Military Officers,” Arthritis Care & Research, vol., pp. 8, 2023.
15. J. F. Griffith, “Five Overlooked Injuries on Knee MRI,” American Journal of Roentgenology, vol. 217, no. 5, pp. 1165-1174, 2021.
16. J. Hietamo et al., “Injury History and Perceived Knee Function as Risk Factors for Knee Injury in Youth Team-Sports Athletes,” Sports Health-a Multidisciplinary Approach, vol. 15, no. 1, pp. 26-35, 2023.
17. Y. Hiranaka et al., “Influence of posterior tibial slope on sagittal knee alignment with comparing contralateral knees of anterior cruciate ligament injured patients to healthy knees,” Scientific Reports, vol. 12, no. 1, pp. 8, 2022.
18. P. M. Holm, E. M. Roos, E. Boyle, and S. T. Skou, “The clinical profile of people with knee osteoarthritis and a self-reported prior knee injury: A cross-sectional study of 10,973 people,” Osteoarthritis and Cartilage, vol. 29, no. 3, pp. 341-345, 2021.
19. N. L. Hunt, M. V. Robinett, and T. N. Brown, “Knee muscle strength and steadiness for individuals with anterior cruciate ligament reconstruction and knee osteoarthritis,” Clinical Biomechanics, vol. 119, pp. 7, 2024.
20. E. Iordache, M. H. Supsup, S. R. Y. Supsup, F. Amsler, and A. Hirschmann, “Kaplan fibers injuries in acute ACL-deficient knees and ACL reconstructed knees - redefining the structure and risk assessment on routine MRI using injury patterns,” Swiss Medical Weekly, vol. 151, pp. 26S-26S, 2021.
21. T. Jiang, F. Feng, Y. Cao, H. T. Yang, and R. S. P. Raj, “Image Segmentation Method for Athlete Knee Joint Injury Using Transformer Model by MIoT,” Brazilian Archives of Biology and Technology, vol. 66, pp. 15, 2023.
22. H. S. R. Jones, V. H. Stiles, J. Verheul, and I. S. Moore, “Angular Velocities and Linear Accelerations Derived from Inertial Measurement Units Can Be Used as Proxy Measures of Knee Variables Associated with ACL Injury,” Sensors, vol. 22, no. 23, pp. 14, 2022.
23. O. I. Kilicoglu, T. Pehlivanoglu, M. Demirel, M. Chodza, H. I. Balci, and M. Asik, “The Impact of the Ligamentous Injury Pattern and Associated Neurovascular Injury on Ultimate Knee Function in Patients with Traumatic Knee Dislocations,” Journal of Knee Surgery, vol. 34, no. 14, pp. 1495-1502, 2021.
24. H. Knapic, E. Shanley, C. A. Thigpen, A. Prats-Uribe, C. D. Fair, and G. S. Bullock, “Impact of Prolonged Sport Stoppage on Knee Injuries in High School Athletes: An Ecological Study,” Journal of Sport Rehabilitation, vol. 33, no. 4, pp. 225-230, 2024.
25. A. P. Kong, R. M. Robbins, J. D. Stensby, and R. D. Wissman, “The Lateral Knee Radiograph: A Detailed Review,” Journal of Knee Surgery, vol. 35, no. 05, pp. 482-490, 2022.
26. M. Krause, T. C. Drenck, L. Eggeling, J. Frings, R. Akoto, and K. H. Frosch, “German S2e-Guideline “Knee Dislocation”,” Zeitschrift Fur Orthopadie Und Unfallchirurgie, vol., pp. 6, 2022.
27. A. Kuwabara, E. Kraus, and M. Fredericson, “Narrative Review - Knee Pain in the Pediatric Athlete,” Current Reviews in Musculoskeletal Medicine, vol. 14, no. 3, pp. 239-245, 2021.
28. C. Y. Le and T. S. Visser, “The fear of developing knee OA after a traumatic knee injury - and how to prevent it?,” British Journal of Sports Medicine, vol. 57, no. 24, pp. 1579-1580, 2023.
29. G. H. Lei, “Application and research of nano-biomaterials in knee cruciate ligament rehabilitation after sports injury,” International Journal of Nanotechnology, vol. 18, no. 1-4, pp. 82-96, 2021.

30. M. Leppänen et al., "Change of Direction Biomechanics in a 180-Degree Pivot Turn and the Risk for Noncontact Knee Injuries in Youth Basketball and Floorball Players," American Journal of Sports Medicine, vol. 49, no. 10, pp. 2651-2658, 2021.