Molecular & Cellular Biomechanics 2024, 21(4), 993.
https://doi.org/10.62617/mcb993

Article

Prevention of knee joint injuries in football basic training under the constraints of biomechanics model

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CITATION

Li J, Fu W. Prevention of knee joint injuries in football basic training under the constraints of biomechanics model. Molecular & Cellular Biomechanics. 2024; 21(4): 993. https://doi.org/10.62617/mcb993

ARTICLE INFO

Received: 4 December 2024
Accepted: 12 December 2024
Available online: 30 December 2024

Abstract: Traditional research on knee injury prevention lacks scientific and targeted research due to the lack of biomechanics quantitative analysis and the failure to fully incorporate the specificity of football, making it difficult to effectively reduce the risk of injuries to athletes. This paper solves the problems of insufficient quantification and lack of specificity in traditional research by introducing a biomechanics model. This paper uses open source 3D modeling software to construct an anatomical model of the knee joint, uses an ordinary camera combined with Kinovea software to analyze the motion trajectory of the knee joint, uses IMU (Inertial Measurement Unit) sensors to collect motion data, and uses OpenSim software to perform force analysis. Based on these analysis results, this paper designs a personalized knee injury prevention training program and conducts a basic training comparison experiment. The medial-lateral stress ratio of the knee joint in the experimental group is eventually reduced to 0.92, which reduces the peak force on the knee joint, improves knee joint stability, and the injury risk score fluctuation decreases during training, with the lowest being 7.3. The results show that the solution proposed in this paper provides scientific, systematic and practical guidance for the prevention of knee injuries in basic football training, and improves the safety and effectiveness of training.

Keywords: biomechanics model; knee injury prevention; motion trajectory analysis; inverse dynamics analysis; personalized training

1. Introduction

In basic football training, athletes need to perform a lot of changes of direction, sudden stops, jumps, etc. These actions put a great load on the knee joint, making the knee joint one of the most vulnerable parts in football. The knee joint is one of the most important joints in human weight-bearing and movement, and knee joint injury becomes a serious problem during training [1,2]. Knee injury will not only lead to a decline in athletes' athletic ability, but may also have a long-term impact on their careers. According to relevant research, the incidence of knee injuries during high-intensity exercise is high, especially anterior cruciate ligament injuries, meniscus injuries, and articular cartilage injuries, which often require long-term rehabilitation treatment and may even lead to irreversible functional impairment [3,4]. The high incidence of knee injuries not only increases the physical burden on athletes, but also poses a huge challenge to the medical and rehabilitation fields. Traditional measures to prevent knee injuries are mainly based on static training methods, which fail to fully consider the individual differences of each athlete and make it difficult to accurately intervene in the load changes of the knee joint [5,6]. Therefore, personalized training programs have gradually become a research hotspot for sports injury prevention.

IMU sensors provide new tools for research in the field of biomechanics [7,8]. The sensors can accurately capture the dynamic data of football players' knee joints during training and competition, providing an objective basis for evaluating the stress of the knee joint and its stability during movement [9,10]. Through detailed analysis of these data, the dynamic changes of the knee joint during movement can be monitored in real time, providing a scientific basis for the formulation of personalized training plans in basic football training. Compared with traditional static training methods, personalized knee joint prevention training programs based on IMU sensor data feedback can dynamically adjust the intensity and content of training, more effectively reduce excessive load on athletes' knee joints, and reduce the risk of injury [11,12]. This study aims to explore the potential of IMU sensor real-time data in reducing the risk of knee injuries in football players by combining it with a personalized knee prevention training program.

The main contributions of this paper are as follows:

(1) The introduction of biomechanics model for quantitative analysis of the knee joint improves the scientificness and pertinence of knee injury prevention in basic football training.

(2) The use of open source 3D modeling software to construct an anatomical model of the knee joint provides an accurate anatomical basis for subsequent motion and force analysis.

(3) Combining high-definition cameras, Kinovea software and IMU sensors, high-precision capture and analysis of knee joint motion trajectory is achieved.

(4) Based on the results of motion and force analysis, a personalized knee injury prevention training program is designed, and its effectiveness is verified through experiments.

2. Related work

The study and prevention of knee joint injuries has become an important research direction in the field of biomechanics and football training [13,14]. The biomechanics model can provide quantitative analysis of force, stability and kinematics by simulating the force conditions of the knee joint during movement [15,16]. In recent years, the application of biomechanics model has gradually become a core tool for studying knee injuries, showing great potential in injury risk assessment and the design of personalized training programs [17,18].

In basic football training, research on the prevention of knee injuries has made some progress. Studies have shown that specific training methods can effectively improve the stability and strength of the knee joint and reduce the possibility of injury [19,20]. Malaichamy [21] studied the comprehensive effects of coordination and balance in preventing and improving injuries among football players. Song 's [22] study analyzed specific high-risk movements in football and reduced the risk of knee injuries by adjusting these movements. However, these studies lacked consideration of individual differences among athletes.

This model has been widely used in the study of biomechanics model to analyze joint forces and movement patterns [23]. The inverse dynamics method can accurately simulate the force distribution of the knee joint in different types of movement and identify those high-risk movement patterns that may cause injury [24]. Some studies have conducted in-depth biomechanics analysis of high-intensity exercises such as jumping and running and found that knee shear force and rotational torque are key risk factors for knee injuries [25,26]. Through these findings, this study aims to further explore how to prevent knee injuries in basic football training through biomechanics model.

In practical applications, knee injury risk assessment based on biomechanics model needs to be combined with sensor technology. IMU sensors can accurately measure the motion parameters of the knee joint and have been widely used. After the data measured by the IMU sensor is input into the biomechanics model, it can evaluate the load state of the knee joint in different movements in real time, and then evaluate the athlete's injury risk. Previous studies have shown that the combination of IMU sensors and biomechanics model can adjust movement patterns in real time during training and reduce sports injuries [27].

In recent years, there have been many studies on knee joint stability and force analysis. Many studies have shown that knee joint stability is not only related to the strength and coordination of the surrounding muscles, but also to the movement trajectory and force distribution of the knee joint. ZhaoriGetu [28] found that biomechanics model can provide data support for the optimization of personalized training programs. In general, by accurately evaluating the stress conditions, movement stability and injury risk of the knee joint, a more scientific and effective training plan can be developed to reduce the risk of knee injury in athletes.

3. Biomechanics analysis methods for preventing knee injuries

3.1. Construction of knee biomechanics model

This paper uses Blender software combined with a public knee joint dataset to construct a three-dimensional biomechanics model of the knee joint [29]. First, this paper obtains three-dimensional data related to the knee joint from The Visible Human Project, and then accurately models the bone structure of the knee joint in the Blender environment based on the actual anatomical connection relationship between the bones.

When creating a knee joint model in Blender, first modeling each bone independently and adjust the relative positions of the bones, as shown in **Figure 1**.

The shape of each bone is adjusted through Blender to ensure its accuracy, and the connection position between bones is defined according to the anatomical structure of the knee joint. After establishing the contact area of the knee joint, the contact surface and friction coefficient between the femur and tibia are set, and the position and dynamic behavior of the patella are accurately represented. Then, the skeletal system of Blender is used to construct the joints and soft tissues. In order to accurately simulate the biomechanics behavior of the knee joint, the soft tissue part of the knee joint was added to the model. The ligaments and tendons were modeled in Blender, and the length and elasticity of the ligaments were defined first when creating the soft tissue. Each ligament is connected to the bone structure through a constraint system, and then a linear deformer is used to simulate the expansion and contraction and tension of the tendon during knee joint movement.

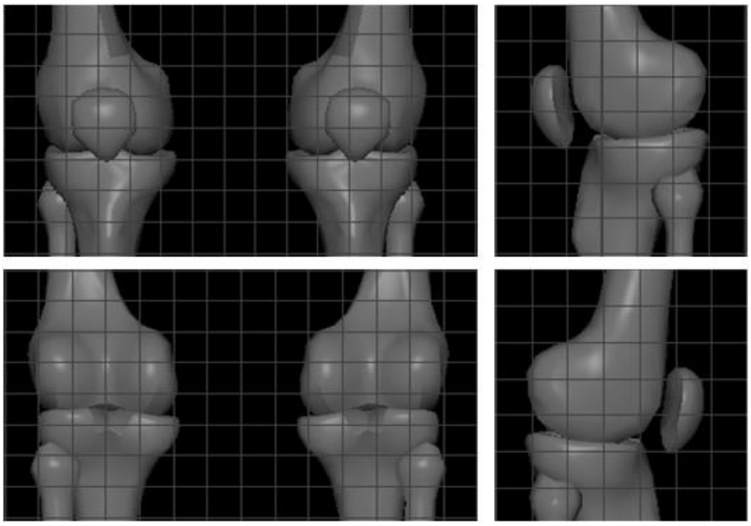

Figure 1. Knee joint bone modeling.

After completing the modeling of bones and soft tissues, the contact mechanical characteristics of the knee joint are simulated using a physical engine. The friction coefficient of the contact surface between the femur and tibia is set to 0.3. The ligaments and tendons are modeled based on their length and elastic modulus parameters, with the elastic modulus of the anterior cruciate ligament set to 500 N/m and the posterior cruciate ligament set to 450 N/m. In the physics engine simulation, the friction coefficient of the knee joint is set to 0.05 and the elastic modulus is set to 1000 N/m^2 to accurately reflect the biomechanical characteristics of the knee joint. In order to simulate the real movement performance of the knee joint in football, animation tools are used for motion simulation in combination with the dynamic load conditions under different movement states.

3.2. Knee joint motion capture and motion data analysis

In order to capture high-precision and comprehensive knee joint motion data, a high-definition camera with 1080p resolution and 60 frames per second was used. The cameras are arranged in frontal and side perspectives to observe the movement trajectory of the knee joint from different angles and provide comprehensive data in three-dimensional space. The front view is mainly used to capture the front and back movement of the knee joint, while the side view is used to record the left and right movement of the knee joint. The camera is arranged parallel to the athlete's movement trajectory, and a fixed distance is maintained between the camera and the sports area during shooting. During this process, the athletes performed typical football actions including jumping, sudden stops, and turns, and each action was performed multiple times in different time periods.

After the camera shooting process is completed, all the collected video data are imported into Kinovea software for the first step of processing [30]. In this software, the knee joint motion trajectory is calibrated and processed, and some annotations are shown in **Figure 2**.

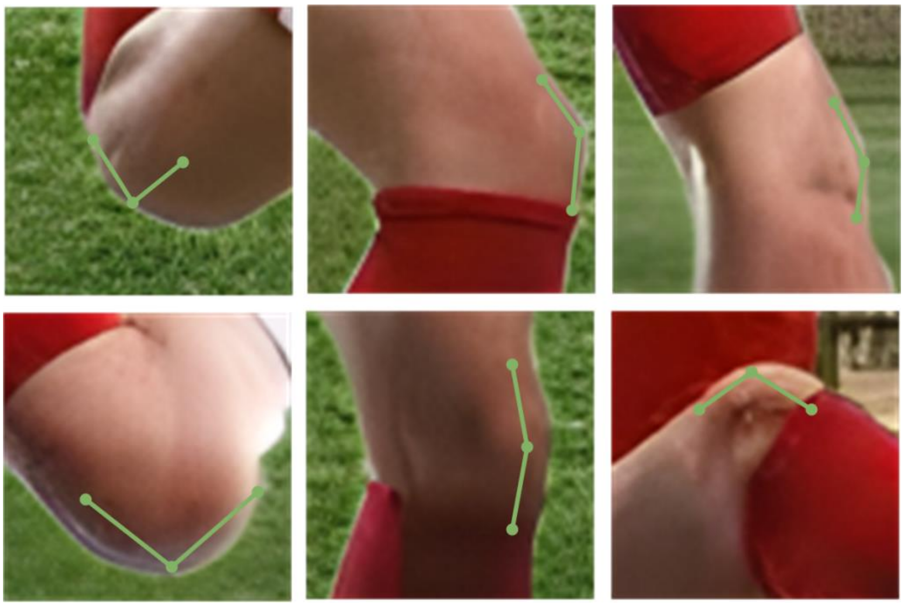

Figure 2. Annotation example.

The knee joint motion data optimization analysis process includes data preprocessing, error correction, data fitting and interpolation, and the final optimization result evaluation. This process is carried out in OpenTrack software. After data collection is completed, the preliminary motion trajectory and joint angle data will be affected by factors such as camera angle deviation and athlete movement error. The processing flow is shown in **Figure 3**.

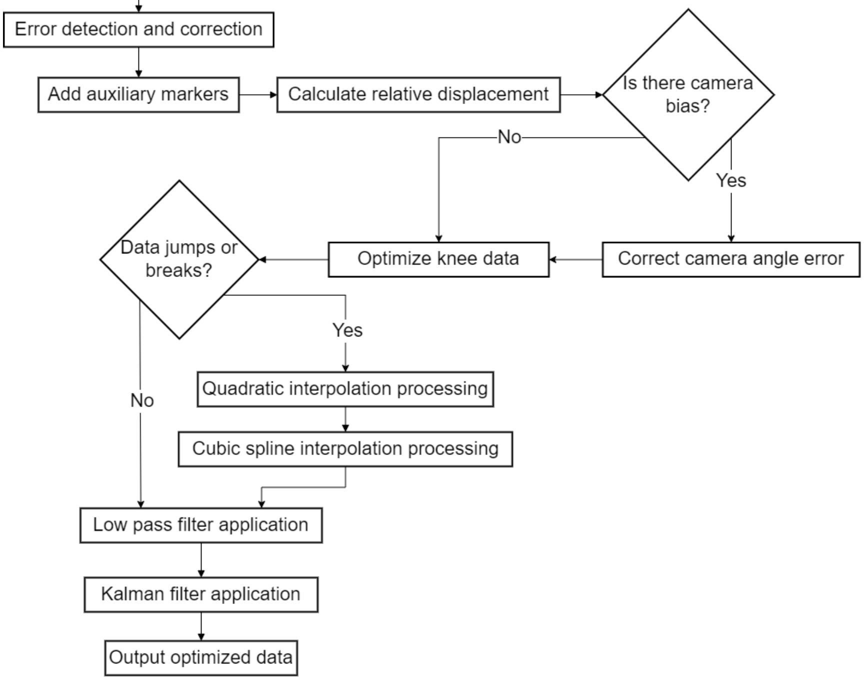

Figure 3. Knee joint motion data analysis process.

The first step in optimizing the analysis process is to perform error detection and correction. The data is imported into OpenTrack software, which calibrates the relative position relationship by adding auxiliary markers to the video. Using these markers, OpenTrack can calculate the relative displacement of the knee joint key points in each frame and correct errors caused by changes in camera perspective or rapid movement of the athlete.

After error correction, the OpenTrack software makes detailed adjustments to the position, speed, and angle changes of the knee joint, gradually eliminating errors in the preliminary data and ensuring the accuracy of the motion trajectory. During this process, OpenTrack not only considers the data in each frame of the image, but also combines the overall characteristics of the athlete's movement trajectory and further optimizes the data by analyzing changes in movement patterns. The goal of this stage is to ensure that the motion trajectory of each marker point is as consistent as possible with the actual motion trajectory, thereby obtaining high-precision motion data.

In the process of optimizing knee joint motion data, OpenTrack uses a variety of interpolation methods to handle data discontinuities and errors. Because data jumps or breaks often occur when the knee joint performs fast, highly dynamic movements, and data jumps are more obvious during jumping, sudden stops, and turns, OpenTrack uses quadratic interpolation and cubic spline interpolation to fill in these missing or discontinuous data. Quadratic interpolation relies on every three adjacent data points when processing data, and fills the data through a quadratic polynomial. Its mathematical expression is:

$$f(x) = a_2x^2 + a_1x + a_0 \quad (1)$$

a_0, a_1, and a_2 are coefficients calculated from known data points.

The calculation speed of secondary paper insertion is fast and suitable for most stable motion trajectories, but it cannot adapt well to drastic motion changes for actions with large dynamic changes.

To better handle these complex dynamic data, OpenTrack uses cubic spline interpolation, which fits multiple data points through polynomials to ensure smooth data and continuous changes in position, velocity, and acceleration. The two interpolation methods are used in combination to automatically select the most suitable algorithm according to the different characteristics of the data.

During the data optimization process, OpenTrack uses low-pass filters and Kalman filters to further smooth the motion data. The role of the low-pass filter is to remove small fluctuations in the acquisition process or noise caused by random sensor errors. By setting a cutoff frequency, the low-pass filter can filter out noise signals that exceed this frequency and retain only low-frequency stable signals. In some high-speed movements or complex dynamic actions such as sudden stops and turns, low-pass filters cannot completely eliminate the instability and errors caused by the movement itself. For this reason, OpenTrack uses Kalman filters. The Kalman filter combines the motion model and observation data to gradually predict and correct data deviations, and can effectively offset the errors caused by rapid movements when processing rapidly changing dynamic data. The combination of the two filtering methods makes the final knee joint motion trajectory data more accurate.

After completing the data optimization, OpenTrack software will output the optimized knee joint motion trajectory and angle change data. After error correction, fitting interpolation and smoothing, these data can more accurately reflect the dynamic changes of the knee joint in different motion stages.

3.3. Knee joint force analysis and high-risk action identification

3.3.1. Implementation of knee joint force analysis

First, a MyoMotion IMU sensor was installed on the outside of the athlete's knee joint to capture the motion of the knee joint. The IMU sensor is mounted on the outside of the knee joint using a bracket and aligned with the rotation axis of the knee joint. The sampling frequency of the sensor is set to 100 Hz.

When athletes perform actions, such as jumping, sudden stops, and turns, the IMU sensor records the acceleration and angular velocity data of the knee joint in real time, and transmits the data to the computer through the wireless communication module. During the data transmission process, the data collected by the sensor is saved in a real-time log file for subsequent analysis. The OpenSim software running on the computer is responsible for receiving this data and performing force analysis. The data transmission process uses low-latency, high-stability wireless technology to ensure that sensor data can be accurately transmitted to the OpenSim software for subsequent processing.

After the data is transferred to the computer, OpenSim builds a virtual knee joint structure based on the 3D anatomical model of the knee joint. Next, OpenSim inputs the motion data obtained from the IMU sensor into the knee joint model.

Before conducting knee force analysis, the time series consistency between the IMU data and the video capture system was ensured by time stamp synchronization. A low-pass filter was then applied to reduce high-frequency noise, and a median filter algorithm was used to remove outliers and outliers. In addition, the IMU sensor data was calibrated using baseline data recorded in a motion-free state to compensate for system deviations. Finally, the missing or discontinuous parts of the data were filled using the cubic spline interpolation method.

The input data includes kinematic parameters such as knee joint angle change, joint rotation angle, acceleration, angular velocity, and linear velocity.

Knee joint angle $\theta(t)$ changes as follows:

$$\theta(t) = \arctan\left(\frac{y_2 - y_1}{x_2 - x_1}\right) \tag{2}$$

$(x_1,\ y_1)$ and $(x_2,\ y_2)$ are the coordinate points of the femur and tibia.

The joint angular velocity $v(t)$ and acceleration $a(t)$ are:

$$v(t) = \frac{d\theta(t)}{dt} \tag{3}$$

$$a(t) = \frac{dv(t)}{dt} \tag{4}$$

The joint linear velocity is:

$$v_{linear}(t) = \sqrt{v_x(t)^2 + v_y(t)^2 + v_z(t)^2} \quad (5)$$

$v_x(t)$, $v_y(t)$, and $v_z(t)$ are the velocity components of the knee joint in each direction in three-dimensional space.

The records of some time points are shown in **Table 1**.

Table 1. Example of IMU sensor raw data.

Timestamp	Acceleration (m/s^2)			Angular Velocity (rad/s)		
	X	*Y*	*Z*	*X*	*Y*	*Z*
1	0.01	−0.02	0.03	0.005	−0.002	0.003
2	0.015	−0.025	0.035	0.006	−0.003	0.004
3	0.02	−0.03	0.04	0.007	−0.004	0.005
4	0.025	−0.035	0.045	0.008	−0.005	0.006
5	0.03	−0.04	0.05	0.009	−0.006	0.007
6	0.035	−0.045	0.055	0.01	−0.007	0.008
7	0.04	−0.05	0.06	0.011	−0.008	0.009
8	0.045	−0.055	0.065	0.012	−0.009	0.01
9	0.05	−0.06	0.07	0.013	−0.01	0.011

These kinematic parameters are the basis for force analysis. OpenSim applies these data to its inverse dynamics algorithm to calculate the mechanical load of the knee joint at different stages of movement. During this process, OpenSim infers the force conditions of various parts of the knee joint, including the femur, patella, tibia and surrounding soft tissues based on kinematic parameters.

OpenSim's inverse dynamics analysis calculates the moment, shear force, compression force and combined force of the knee joint at every moment by inputting kinematic parameters and combining them with biomechanics data. For the internal and external forces of the knee joint, OpenSim provides detailed dynamic force data by analyzing different mechanical directions. During an emergency stop, the knee joint will be subjected to a large shear force. OpenSim can accurately identify and calculate the medial and lateral pressure distribution of the knee joint at this moment, further revealing the force differences in various parts of the knee joint during dynamic movement.

During exercise, the force applied to the knee joint is not static, but changes with each stage of the exercise. When jumping, the forces on the knee joint are different during take-off and landing. OpenSim can accurately capture this change and provide real-time force calculation data for each action stage. By analyzing the forces on the knee joint at different time points, OpenSim can reveal which stages of the movement produce excessive loads, especially stress concentration areas during high-intensity movements.

3.3.2. Implementation of high-risk action recognition

In OpenSim, the received motion data is used to drive the virtual knee joint model to identify high-risk actions. The detailed process is shown in **Figure 4**.

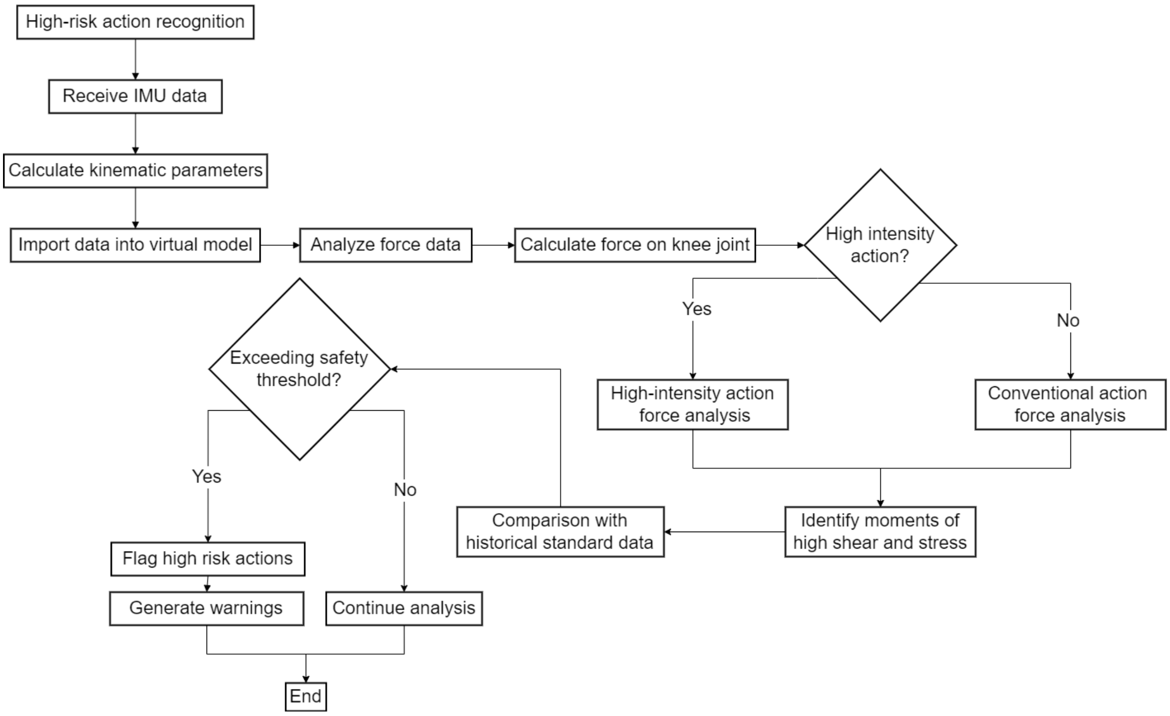

Figure 4. High-risk action recognition process.

OpenSim uses IMU data to calculate parameters such as the joint angle, angular velocity, and acceleration of the knee joint at different time points. Next, OpenSim uses inverse dynamics methods to perform force analysis based on these kinematic parameters to simulate the mechanical loads on the knee joint at each stage of movement.

In jumping and sudden stop movements, the knee joint will be subjected to large shear force and pressure at the moment of contact with the ground or sudden stop. OpenSim calculates the torque, shear force and pressure of various parts of the knee joint based on the input data. Since the load on the knee joint is usually concentrated in certain moments or movement phases during these movements, OpenSim analyzes the mechanical load at each phase and identifies the moments of high shear force and high pressure on the knee joint.

The high-risk action recognition function of OpenSim is based on the comparison of the mechanical load data of the movement phase with the historical standard action data. When athletes are performing actions such as turning, jumping or sudden stops, OpenSim will compare the current motion data with the force data of historical standard actions in real time to detect whether the load exceeds the standard. Specifically, when the shear force, rotational torque, or joint angle change at a certain moment or a certain movement stage exceeds the safety threshold of historical data, the movement stage will be marked as a high-risk action.

In order to accurately identify high-risk movements, OpenSim also uses model optimization to adapt to the movement characteristics and postures of different athletes. During the simulation process, the system adjusts the knee joint model in real time, dynamically monitors the athlete's movement trajectory, and analyzes the force data of each movement stage. During turning movements, the knee joint often encounters large medial and lateral shear forces, especially at the moment of turning.

OpenSim can identify these moments and accurately calculate the changes in rotational torque, shear force, and joint angle, thereby automatically identifying which movement phases have a higher risk of injury.

When OpenSim identifies a certain movement phase as high risk, the system will generate warning data to remind coaches and athletes that there is a potential risk of overload in this movement. In this way, OpenSim helps athletes and coaches identify and adjust unsafe movements in a timely manner, thereby avoiding the risk of knee injuries caused by excessive load or improper movement. In subsequent training, these high-risk movements will be used as a reference to guide athletes to adjust their exercise postures and avoid knee injuries.

3.4. Personalized training program design

In the personalized training program design, squats and single-leg stabilization training were selected as basic movements. During the design process, virtual simulation software is mainly used in combination with a three-dimensional anatomical model of the knee joint to simulate the stress conditions of the knee joint in different stages of movement, and this data is used to adjust the training movements to ensure that the load on the knee joint during training is reduced as much as possible.

In the design of the squat action, Blender is used to simulate the force distribution of the knee joint at different bending angles and squat depths. During the squat process, the bending angle of the knee joint and the depth of the squat are the key factors affecting the force. Through simulation, it is found that when the bending angle of the knee joint is larger, the load on the inner side increases significantly, and the load on the outer side is smaller. Especially when the knee joint is at a larger bending angle, the pressure on the soft tissues and bones on the inside of the knee joint will be more concentrated, which may lead to the risk of medial injury. When the knee angle is smaller, the load on the knee joint is more evenly distributed, but the effect of the movement is not as good as a deeper squat. Therefore, the goal in design is to optimize the squat angle and keep the knee flexion angle between 45 degrees and 75 degrees, which can avoid excessive load and achieve the effect of strengthening the knee joint.

For single-leg stability training, the design also uses Blender to simulate the force distribution of the knee joint at different support angles. When supporting one leg, the outer side of the knee joint is subjected to greater shear force. Simulation shows that when the knee joint angle of the supporting leg is less than 20 degrees, the load on the outside of the knee joint increases significantly. Therefore, the knee joint angle of the supporting leg is kept between 20 degrees and 30 degrees.

The personalized training plan includes squats, single-leg stability, lateral movement and balance mat exercises. Squats are performed in groups of 8 to 12 times, for a total of 3 sets; single-leg stability exercises are performed in groups of 30 seconds on each leg, for a total of 3 sets; lateral movement exercises are performed in groups of 5 min each, for a total of 2 sets; single-leg standing on the balance mat for 45 seconds, for a total of 3 sets. Training is performed four times a day, and each training session lasts 30 min.

In order to ensure that the training movements can effectively reduce the load on the knee joint, an IMU sensor is also added to the design to monitor the movement status of the knee joint in real time. The IMU sensor is installed on the outside of the athlete's knee joint to collect acceleration, angular velocity and angle data of the knee joint in real time. For example, in squat training, the IMU sensor can capture the acceleration and angular velocity changes of the knee joint in real time. During the squat process, the sensor detects the force of the knee joint at different depths. During training, athletes adjust the squat depth based on the real-time data fed back by the IMU.

In order to comprehensively evaluate the effectiveness of personalized training programs, this study used a 5-point scale questionnaire filled out after training to assess comfort, pain, and fatigue. The specific content of each training and the athlete's experience were recorded in detail through training logs.

To ensure the effectiveness and adaptability of the training plan, this study used IMU sensors to monitor the force and movement patterns of the athlete's knee joint in real time, and dynamically adjusted the training plan in combination with biweekly biomechanical assessments. At the same time, subjective feedback from athletes was collected regularly to adjust the training load or content. If an athlete showed signs of injury, the training plan was adjusted immediately to increase restorative training and treatment measures. In addition, the athlete's adaptability to training intensity was evaluated by monitoring physiological indicators such as heart rate and blood lactate levels, and the training load model was used to balance the training volume and recovery time. The athlete's psychological state was also regularly evaluated to adjust the training content. An adaptive feedback loop was established to adjust the training intensity and recovery time according to physiological stress or psychological fatigue, and adaptive changes were tracked over a long period of time to adjust the training cycle and content accordingly.

4. Evaluation of the effect of knee injury prevention program

In this experiment, 20 healthy athletes were randomly divided into an experimental group and a control group, with 10 people in each group undergoing basic training. The experimental group received a personalized knee joint prevention training program within 3 weeks, and the training process was dynamically adjusted based on the knee joint angle, acceleration and angular velocity data fed back by the IMU sensor in real time. The control group followed a standard training program without personalized adjustments. They trained 4 times a day, 30 min each time, and the daily training data was recorded and statistically analyzed every 3 days.

4.1. Stress distribution of the knee joint

The stress distribution of the knee joint is usually analyzed by the medial and lateral stress values and their ratio. These indicators represent the difference in load between the inside and outside of the knee joint at different stages of exercise or training, and thus assess whether the load is uniform. The average stress of the experimental group and the control group at each time is shown in **Table 2**.

Table 2. Analysis of medial and lateral stress of knee joint.

Time Point	Group	Before Training			After Training		
		Inside Stress (N/m^2)	**Outside Stress (N/m^2)**	**Medial-Lateral Stress Ratio**	**Inside Stress (N/m^2)**	**Outside Stress (N/m^2)**	**Medial-Lateral Stress Ratio**
1	Experimental Group	348.12	251.65	1.38	335.88	269.45	1.25
	Control Group	352.3	244.82	1.44	350.25	249.6	1.4
2	Experimental Group	340.5	259.72	1.31	328.17	274.81	1.19
	Control Group	336.75	261.19	1.29	334.21	258.23	1.29
3	Experimental Group	330.42	265.56	1.25	320.5	279.23	1.14
	Control Group	329.14	258.48	1.27	326.1	263.35	1.24
4	Experimental Group	322.18	275.04	1.17	311.98	286.02	1.09
	Control Group	334.8	265.23	1.26	332.7	267.5	1.24
5	Experimental Group	317.35	280.71	1.13	307.24	295.1	1.04
	Control Group	330.4	270.86	1.22	325.12	271.65	1.2
6	Experimental Group	308.94	291.3	1.06	299.67	305.4	0.98
	Control Group	323.58	274.11	1.18	318.02	282.09	1.13
7	Experimental Group	298.72	303.21	0.99	290.12	314.08	0.92
	Control Group	317.83	281.45	1.13	312.56	286.72	1.09

Table 2 shows the changes in knee joint force in the experimental group and the control group before and after training. After personalized training, the internal and external stresses of the experimental group gradually tend to be balanced, and the ratio of internal and external stresses decrease. In the first statistics, the ratio drops from 1.38 before training to 1.25 after training, and in the seventh statistics, it drops to 0.92. The control group shows smaller changes, with a smaller decrease in the medial-lateral stress ratio than the experimental group, suggesting that personalized training reduced uneven loading of the knee joint.

4.2. Peak force on the knee joint

The peak force on the knee joint is evaluated by shear force, compression force and rotational moment to reflect the maximum mechanical load on the joint. Analyzing its changes can evaluate the optimization effect of the training program on the knee joint load and verify the advantages of personalized training in reducing the risk of injury and improving joint mechanical properties. The specific situation is shown in **Table 3**.

Table 3 shows the changes in the peak values of knee shear force, compression force, and rotational moment during training in the experimental and control groups. The peak shear force of the experimental group decreases from 50.2 N to 44 N, the compression force decreases from 120.1 N to 112.5 N, and the rotational torque decreases from 35.5 N·m to 31.7 N·m The knee joint load is reduced more significantly than that of the control group. The data show that personalized training programs are more effective in reducing knee joint load and reducing the risk of injury.

Table 3. Peak force on the knee joint.

Time Point	Group	Peak Shear Force (N)	Peak Compression Force (N)	Peak Rotation Torque (N·m)
1	Experimental Group	50.2	120.1	35.5
	Control Group	53.5	125.8	37.5
2	Experimental Group	49.8	119.5	34.9
	Control Group	52.8	124.5	37.2
3	Experimental Group	48.6	118.1	34.2
	Control Group	52	123.5	36.8
4	Experimental Group	47.8	116.9	33.6
	Control Group	51.5	122.6	36.5
5	Experimental Group	46.5	115.3	33
	Control Group	51	121	36.2
6	Experimental Group	45.2	113.8	32.4
	Control Group	50.2	119.6	35.8
7	Experimental Group	44	112.5	31.7
	Control Group	49.5	118	35.1

4.3. Knee joint stability

Knee joint stability is assessed by knee joint swing angle and joint excursion, which reflects the control ability of the knee joint. Improving the stability of the knee joint can reduce the risk of injuries caused by unstable movements. Especially in the training of athletes, personalized training programs can significantly improve the stability of the knee joint. The specific situation is shown in **Figure 5**.

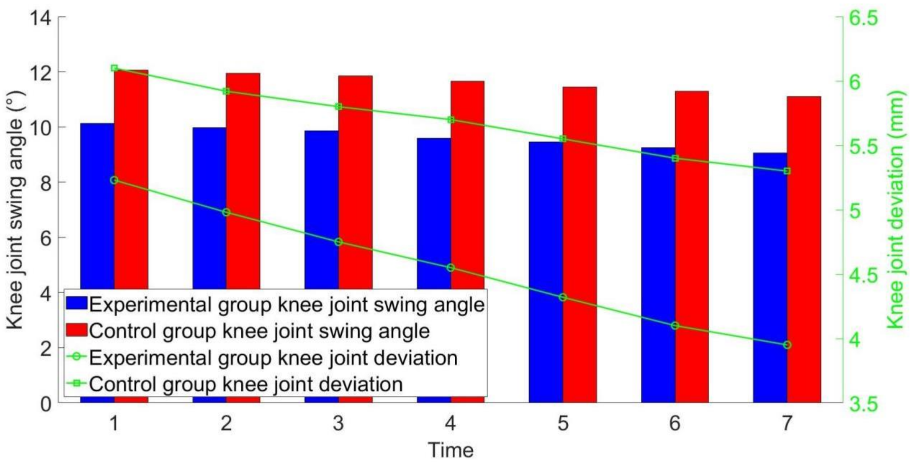

Figure 5. Knee stability assessment.

The data in **Figure 5** show that the knee swing angle and deviation of the experimental group show significant improvements, with the swing angle decreasing from 10.12° to 9.05° and the deviation decreasing from 5.23 mm to 3.95 mm. The control group has a smaller change in knee swing angle and deviation, which suggests that personalized training can better control knee stability and reduce the risk of sports injuries.

4.4. Athlete perception and comfort

Athlete perception and comfort are evaluated through four indicators: discomfort, pain, fatigue and comfort, as shown in **Table 4**.

Table 4. Athletes' perception and comfort ratings.

Rating Categories	Experimental group		Control group	
	Average Value	Standard Deviation	Average Value	Standard Deviation
Discomfort Rating	1.94	0.3	3.31	0.42
Pain Rating	1.75	0.33	3.17	0.45
Fatigue Rating	2.04	0.29	3.31	0.38
Comfort Score	3.57	0.42	2.79	0.5

The data in **Table 4** shows that the scores of the experimental group are significantly lower than those of the control group, indicating that personalized knee joint preventive training effectively improves the athletes' knee joint feeling. The experimental group scores discomfort as 1.94, pain as 1.75, fatigue as 2.04, and comfort as 3.57, while the control group scores as 3.31, 3.17, 3.31, and 2.79, respectively. These differences suggest that personalized training can reduce knee discomfort, pain, and fatigue, and improve comfort.

4.5. Knee joint injury risk score

The knee injury risk score combines the analysis results of knee joint force and movement stability, converts key indicators into risk scores, and conducts a comprehensive evaluation based on the weights set by statistical data to finally obtain a score. The scoring standard is 1–10 points. The injury score after training is shown in **Figure 6**.

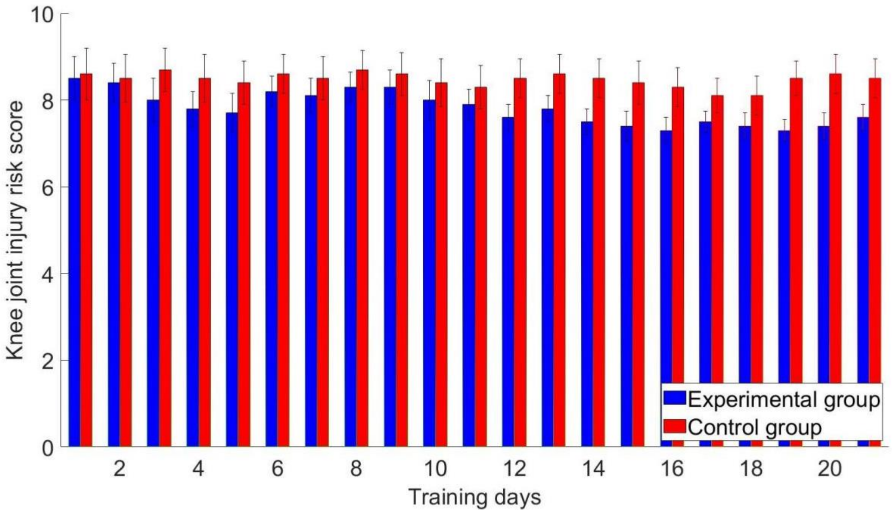

Figure 6. Knee injury score.

Figure 6 shows the changes in knee injury risk scores in the experimental and control groups during the 21-day training. The injury risk score of the experimental group gradually fluctuates and decreases from 8.5 to a minimum of 7.3. The scores of the control group fluctuates between 8.1 and 8.7. The error bars represent the standard deviation of the daily data, and the fluctuation of the experimental group data is smaller than that of the control group. The data show that personalized training can reduce the risk of injury.

5. Discussion

This study proposed a personalized knee injury prevention training program through biomechanical model and IMU sensor technology, and empirically verified it in basic football training. The results showed that the program can significantly reduce the mechanical load of the knee joint, improve joint stability, and enhance the comfort of athletes, reducing the risk of knee injury. The key findings of the study are discussed in depth below.

The theory of personalized training program comes from the intersection of sports biomechanics and sports training. Sports biomechanics provides quantitative analysis of knee joint movement and force, revealing the changes in mechanical load and joint stability during exercise, while sports training provides a framework for training intervention, guiding how to optimize athletes' performance and reduce the risk of injury through specific training movements and loads. The mechanism of training effect involves the improvement of muscle strength, the enhancement of joint stability and the improvement of motor control. Through personalized training, athletes' muscle strength has been enhanced and the risk of injury has been reduced. This study not only focuses on the biomechanical changes of the knee joint, but also comprehensively evaluates the training effect, including the subjective feelings and sports performance of athletes, through questionnaires and interviews. This multi-dimensional evaluation method provides a more comprehensive perspective to evaluate the effect of the training program.

Further analysis of the effect changes in different training stages can reveal the key turning points in the training adaptation process and provide a basis for the adjustment of the training plan. In this study, the comparison of data before and after training showed the positive effect of the personalized training program. In the later stage of training, the athletes' knee stability and strength were significantly improved.

The feasibility of the personalized training plan was experimentally verified. The demand for training resources and the acceptance of coaches and athletes were all within an acceptable range, indicating that the training plan has a high feasibility in practical application. The safety assessment showed that the personalized training plan has a positive effect in reducing the risk of injury, and the risk during training was effectively controlled.

There are differences in training effects among athletes of different technical levels, ages, and genders. Future research should further explore how these individual differences affect the training effect so as to formulate personalized training plans more accurately. The changes in knee biomechanics and improved sports performance that may be brought about by long-term adherence to personalized training are important directions for future research. Although the training cycle of this study was 3 weeks, the short-term training effect can predict that long-term adherence to personalized training can further improve the stability and strength of athletes' knee joints. In future studies, the long-term training effect will be tracked and evaluated to verify this prediction.

6. Conclusion

This study constructed a three-dimensional anatomical model of the knee joint by introducing biomechanics model and IMU sensor technology, and designed a personalized knee injury prevention training program. Experimental verification has shown that this solution reduces the mechanical load on the knee joint, improves joint stability, enhances the comfort of athletes, and reduces the risk of knee joint injury. However, the research sample size is limited, and future work needs to expand the sample and further explore the personalized training effects under different sports characteristics, in order to provide more comprehensive scientific guidance for knee joint protection in basic football training.

Author contributions: Conceptualization, JL; methodology, WF; data curation, JL; writing—original draft preparation, JL; writing—review and editing, WF; funding acquisition, JL. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Heilongjiang Province Provincial Universities Basic Research Funds Research Project (project number: 145109162); This research was funded by Degree and Graduate Teaching Reform Project of Qiqihar University (project number: QUZLTS_JG2023027).

Ethical approval: Not applicable.

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

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