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Article

Study on the biomechanical mechanism of ankle joint injury in martial arts and application of tissue engineering bone repair materials

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Abstract: As a high-intensity competitive sport, martial arts has high explosive power and complex joint movement patterns. Ankle injury is one of the common sports injuries. This paper analyzes the mechanism of ankle injury and the influence of relevant mechanical factors on ankle injury in combination with the biomechanical characteristics of martial arts movements. At the same time, with the continuous development of biomedical engineering, the application of tissue engineering bone repair materials in bone injury repair has received widespread attention. This paper focuses on applying tissue engineering bone repair materials after ankle injury in martial arts sports and analyzes its biocompatibility, mechanical properties, and clinical effects in the bone repair process. Studies have shown that tissue engineering materials can effectively promote bone regeneration, accelerate healing, and show good prospects in reducing the recovery period of athletes. Finally, this article proposes the future application prospects and development direction of tissue engineering bone repair materials in martial arts sports injury repair.

Keywords: ankle injury; biomechanical mechanism; tissue engineering; bone repair materials; sports injury repair; biocompatibility; mechanical properties

1. Introduction

In modern martial arts, the ankle joint [1,2] has become a common site of sports injury because it is subjected to high-intensity impact and torsional loads. Martial arts movements have strong explosive power and involve complex movements such as rapid turning, jumping, and kicking. These movements often exert a lot of stress on the ankle joint in a short time. Especially under asymmetric impact, the joint and surrounding soft tissue [3,4] are prone to injury. Ankle joint injuries [5,6] not only affect the athlete's competitive performance but also may lead to chronic pain, joint dysfunction, and even long-term decline in athletic ability if they are not repaired promptly and effectively. The joint motion trajectory, mechanical parameters, and instantaneous impact load in martial arts movements [7,8] play an important role in ankle joint injuries. However, there is a relative lack of research on the biomechanical mechanism of ankle joint injuries in martial arts. Therefore, studying the biomechanical characteristics of martial arts movements and their impact on ankle joint injuries will not only help to reveal the intrinsic mechanism of sports injuries but also provide a theoretical basis for subsequent sports injury prevention and rehabilitation treatment. With the continuous advancement of biomedical engineering technology, tissue engineering bone repair materials [9,10] as a new bone repair method have made certain progress in fracture treatment [9,11] and joint injury repair. Composite scaffold materials with good biocompatibility and mechanical properties, combined with the special sports characteristics of martial arts athletes, can be used to study bone repair after ankle injury, which has important clinical application value and broad prospects.

The main contribution of this study is to deeply explore the biomechanical mechanism of ankle injury in martial arts movements and propose an innovative bone repair scheme. Through a detailed analysis of the force characteristics of the ankle joints of martial arts athletes, new theoretical support is provided for the occurrence mechanism of sports injuries. This paper innovatively combines 3D printing technology with tissue engineering bone repair materials, designs and manufactures a composite scaffold containing hydroxyapatite and polylactic acid, and successfully uses it to repair ankle injuries of martial arts athletes. Through in vitro cell experiments, mechanical properties tests, and animal experiments, the effect of the scaffold material in promoting bone regeneration and accelerating healing was verified, and it showed good biocompatibility and mechanical stability. Studies have shown that the HA/PLA composite scaffold can not only effectively promote new bone formation but also shorten the recovery period of athletes to a certain extent, providing martial arts athletes with a safer and more efficient rehabilitation treatment plan. In addition, the in-depth discussion of material properties and clinical applications in this paper provides a theoretical basis and experimental data for the future application of tissue engineering bone repair materials in sports injury repair, which has high academic value and clinical application prospects.

2. Related work

In recent years, with the rapid development of sports medicine and biomechanics, many scholars have explored the biomechanical mechanisms of sports injuries, especially the occurrence of joint injuries under high-intensity exercise. Ankle joint injuries [2,12] are common sports injuries, especially in high-impact sports such as martial arts, basketball, and football. The root cause of ankle injuries is closely related to excessive joint load, torsional torque, and asymmetric movement patterns. Scholars have revealed the distribution of joint stress in different sports movements through motion capture technology, force platform testing, and finite element analysis. In particular, in movements such as twisting and jumping, the instantaneous high-impact force borne by the ankle joint will cause excessive friction on the joint surface and local compression of the joint surface, which will, in turn, cause injuries such as bone fractures, cartilage damage, or ligament strain. The stress conditions of the ankle joints of basketball players were studied based on three-dimensional motion capture and finite element analysis methods. The results showed that the reaction force suffered by the ankle joint when jumping and landing was the main cause of injury. Through biomechanical analysis of the ankle joints of football players [13,14], it was further confirmed that rotational movements and asymmetric gait pose a high risk of ankle injuries. Although there are a lot of biomechanical studies on ankle injuries, the research on the impact and injury mechanism of the ankle joint caused by the special characteristics of high-intensity explosive movements such as martial arts [15,16], especially rapid turning, kicking, and other movements, is still relatively scarce. Combining the biomechanical characteristics of martial arts movements and conducting in-depth exploration is urgent. Therefore, this study will reveal the biomechanical mechanism of ankle injuries in martial arts through a detailed analysis of martial arts movements, combined with high-precision motion capture and finite element models, to provide theoretical support for preventing sports injuries.

With the rapid development of tissue engineering technology, more and more research focus on using new materials to repair sports injuries, especially in bone injury repair. Traditional fracture repair methods [17,18] mainly rely on internal fixation and autologous bone transplantation, but these methods often have problems such as long postoperative rehabilitation periods and many complications. In recent years, tissue engineering bone repair materials [19,20] have gradually become a research hotspot in the field of sports medicine. Researchers have developed a variety of new bone repair materials, such as hydroxyapatite, polylactic acid, polyvinyl alcohol, etc. These materials have good prospects in promoting bone healing and enhancing bone strength. In particular, the emergence of 3D printing technology has made the design of bone repair materials more precise, and personalized scaffolds can be customized according to individual differences of patients. HA/PLA composite materials [21,22] showed good biocompatibility and osteoinduction ability in vitro experiments, which can effectively promote the regeneration of bone tissue. The recovery speed of patients with porous bone repair scaffolds was significantly improved. At the same time, finite element analysis, as an effective mechanical analysis tool, can simulate the stress behavior of different bone repair materials in vivo and further optimize the repair plan [23,24]. Although some studies have explored the application of tissue engineering materials in bone repair, there is still a lack of systematic research on how to use these materials in the repair of ankle injuries after high-intensity exercise, especially in martial arts athletes. This paper will innovatively combine 3D printing technology and HA/PLA composite materials to design and optimize bone repair materials for ankle injuries of martial arts athletes, aiming to improve bone repair efficiency, shorten the recovery period of athletes, and provide new solutions for sports injury repair.

3. Experimental materials and methods

3.1. Subject recruitment and experimental design

This study plans to recruit 10 athletes (half male and half female) with intermediate and advanced training levels from school teams and professional martial arts training bases. The selection criteria for the subjects are:

Age range: The subjects are between 18 and 30, ensuring the athletes have a certain physical foundation and physiological maturity.

Training level: All subjects are athletes who have received systematic martial arts training for at least 3 years and have certain competition experience and competitive level. In order to ensure the validity and representativeness of the research data, athletes should have intermediate and advanced martial arts skills, complete complex martial arts movements, and have high athletic ability.

Physical screening: Before officially participating in the trial, all subjects must undergo a strict physical examination and medical screening to ensure that they have no history of congenital abnormalities, inflammation, or lesions in the ankle joint and no other recent lower limb injuries (such as ankle sprains, fractures, etc.). Physical screening can exclude experimental errors caused by congenital structural problems or recent injuries and ensure the accuracy of the research results.

Informed consent: All subjects must sign an informed consent form before participating in the experiment, confirming their willingness to participate in the experiment and clearly understanding the risks and precautions during the experiment.

The test movements are designed to simulate the high-intensity and complex movements that martial arts athletes may encounter in actual training and competition to accurately evaluate the force characteristics and potential injury mechanisms of the ankle joint in these movements. Considering that martial arts movements have strong explosive power and high dynamic characteristics, the following typical movements were selected:

Landing after a jump simulates a common jumping or flying action in martial arts. Athletes need to land quickly from the air, and the ankle joint will be subjected to a huge reaction force during the action. In order to ensure the comprehensiveness of the data, two situations were designed: Landing with both feet synchronously and landing with one foot to evaluate the impact of different landing methods on the force of the ankle joint. Landing with both feet synchronously helps to disperse the landing force, while landing with one foot will produce a higher single-point load, which may cause excessive load on the joint. Each landing action will be repeated 3–5 times to ensure the stability and comparability of the data.

3.2. Data collection and preprocessing

In order to ensure the accuracy of the captured data, the acquisition frequency of the camera is set to 200 Hz to capture the rapid changes and subtle movement trajectories of the athletes' movements. In order to eliminate the interference of external light sources on data acquisition, the sports field will use professional light source configuration to ensure that each camera can work stably in a high-light environment. The data collected by the Vicon system can provide multiple parameters such as the motion trajectory, joint angle, and movement speed of each part of the athlete during the experiment. These data will become the basis for analyzing the ankle joint's force characteristics and injury mechanisms.

The ankle joint is shown in **Figure 1**.

Figure 1. Ankle joint display.

In order to accurately evaluate the dynamic load and reaction force on the ankle joint of athletes when performing test movements, this study set up a force platform at the landing point. The sampling frequency of the force platform is set to ≥ 1000 Hz, which can capture the reaction force data of athletes when they land with high precision. In martial arts movements such as landing after jumping and rapid changes in direction, the force platform can record the vertical force, horizontal force, and shear force at the moment of landing in real-time, helping to study the maximum load on the ankle joint at the moment and the change in force. In addition, the force platform can work synchronously with the motion capture system to achieve accurate pairing of motion data and mechanical data, further improving the accuracy of the analysis.

Electromyographic signals are achieved through a surface electromyographic system, which monitors the muscles' activation in ankle stabilization during exercise (such as the gastrocnemius, tibialis anterior, and long toe extensor). Electromyographic signals provide information about muscle activity and fatigue status, which helps understand muscle co-contraction's role in ankle stability. In the experiment, surface electrodes will be attached to the relevant muscle groups to collect electromyographic signals at different stages of exercise. The activation pattern, stability, and regulatory effect of muscle groups on joint loads are further revealed by analyzing the intensity, time domain, and frequency domain characteristics of these signals.

3.3. Finite element modeling

In order to simulate the biomechanical behavior of the ankle joint accurately, this study used high-resolution CT scanning technology to obtain image data of the ankle joint area, and Mimics software was used to reconstruct the three-dimensional geometric model. CT scanning can provide detailed bone tissue structure information, and the accuracy is usually between 0.1 and 0.5 mm, thus ensuring that the reconstructed bone model has high resolution and accuracy. During the image data processing, Mimics software segmented the bone structure and soft tissue (such as muscles, ligaments, etc.) in the original CT image to generate a three-dimensional geometric model of the ankle joint area. These models include bone parts such as the tibia, talus, and fibula, as well as the main soft tissue structures, ensuring accurate geometric information for finite element analysis.

Each structure in the model (bone, soft tissue, etc.) will be assigned appropriate material parameters based on existing literature and experimental data. Common material parameters include elastic modulus and Poisson's ratio, essential for finite element analysis. The elastic modulus of bone is between 10 and 30 GPa, while the elastic modulus of soft tissues such as ligaments and muscles are lower, 10–200 MPa. The Poisson's ratio of the material is between 0.3 and 0.4. The material parameters of the tibia and fibula adopt properties similar to those of human bones, and the talus is assigned corresponding biomechanical parameters based on its contact properties with the surrounding cartilage.

Based on the previous motion capture and force platform data, dynamic loading conditions and boundary constraints suitable for this research goal are set. The motion capture system provides parameters such as the ankle joint's trajectory, velocity, acceleration, etc., during various martial arts movements (such as jumping, landing, kicking, etc.). With this data, the model's boundary conditions and dynamic loads can be set, such as the reaction force when landing or the instantaneous impact force when kicking.

A smaller time step is used for dynamic analysis in terms of loading conditions, especially for instantaneous high-impact loading. This is because high-impact loads usually last for a short time. However, the stress and acceleration they produce may be very large, requiring a higher time resolution to capture these rapidly changing mechanical behaviors. By selecting an appropriate time step, the accuracy of numerical simulation can be improved.

After completing the model establishment and loading condition setting, finite element analysis is performed to solve the stress and strain distribution of the ankle joint under different movements. Finite element analysis is a powerful numerical simulation tool that can accurately calculate the structure's stress, strain, and displacement under external loads.

The basic principle of finite element analysis is based on the Lagrange equation, and the key is to solve the equilibrium equation of the structure under a given load.

$$\sigma = E \cdot \varepsilon \quad (1)$$

In Equation (1), σ represents stress, E is the elastic modulus, ε and is strain. Poisson's ratio is related to the stress-strain relationship and is closely related to volume change and deformation and is used to calculate deformation and displacement:

$$\varepsilon = \frac{1}{E}\left(\sigma - \nu \cdot \sigma_{\mathrm{eq}}\right) \quad (2)$$

In the finite element analysis process, the stress and strain distribution of each part of the model under the loading condition is calculated through node division, element establishment, and equation solving. The calculation of each element is solved through its stiffness matrix and external force matrix. The basic equation is:

$$K \cdot u = F \quad (3)$$

In Equation (3), K is the stiffness matrix, u is the displacement vector, F and is the external force vector.

For simulations of high-impact loading, nonlinear analysis is used to consider the plasticity, crack propagation, and other complex behaviors of the material. The time step is set to a small value to improve numerical accuracy and ensure that no numerical instability occurs during the analysis. By gradually advancing the time step, the mechanical behavior during the dynamic process is accurately captured.

4. Preparation and evaluation of tissue engineering bone repair materials

4.1. Material preparation and scaffold design

In this study, two materials were selected as the core raw materials for bone repair scaffolds: polylactic acid (PLA) and hydroxyapatite (HA).

Porosity is a parameter that describes the ratio of voids to total volume in a scaffold and is calculated using the formula:

$$\phi = \frac{V_{\text{void}}}{V_{\text{total}}} \quad (4)$$

In Equation (4), ϕ is the porosity, V_{void} is the void volume in the scaffold, and V_{total} is the total volume of the scaffold.

The stiffness of the bracket is closely related to the elastic modulus and geometry of its material. The elastic modulus is a measure of the material's ability to resist deformation. The stiffness of the bracket is expressed as:

$$K = E \cdot \frac{A}{L} \quad (5)$$

The degradation rate of polylactic acid is affected by factors such as material properties, external environment, and molecular weight of the material. The degradation rate is:

$$k = A \cdot e^{-\frac{E_a}{RT}} \quad (6)$$

In Equation (6), k is the degradation rate constant, R is the gas constant, and T is the temperature.

The printed scaffold will be surface treated to further improve its surface properties. Through plasma surface treatment or chemical modification, the roughness of the scaffold surface can be significantly improved, which is crucial for cell adhesion and growth. Plasma treatment can improve the hydrophilicity of the material surface, increase surface energy, and promote cell attachment and expansion. At the same time, chemical modification can further enhance the interaction between the scaffold and cells by introducing specific bioactive groups.

4.2. In vitro cell experiments

This study selected rat or human bone marrow mesenchymal stem cells (BMSCs) as the experimental cell source because of their good proliferation ability and multidirectional differentiation potential. Cell culture was carried out at 37 °C and 5% CO_2, using α-MEM medium containing 10% fetal bovine serum (FBS) to provide the necessary nutrients and growth factors to support the growth and division of BMSCs. The fetal bovine serum supplemented in the culture medium provides cells with growth factors, hormones, and other essential nutrients to ensure that cells obtain optimal growth conditions in a suitable environment.

During the cell seeding process, BMSCs were seeded on the pre-sterilized HA/PLA composite scaffold at a 1×10^5 cells/cm^2 density. This density can ensure a sufficient cell number for subsequent cell adhesion and proliferation evaluation. In order to evaluate the effect of scaffold materials on cell behavior, plate culture was set up as a control group to compare the cell adhesion, proliferation, and differentiation of different materials.

Cell adhesion and proliferation were evaluated using a CCK-8 kit. This kit can reflect cell proliferation by detecting cell metabolic activity. At different time points (6 h, 12 h, 18 h, 24 h, 30 h, 36 h, 42 h, and 48 h), after each sampling, CCK-8 reagent was added, and a spectrophotometer measured the absorbance value (450 nm) to calculate the cell proliferation rate. This method can accurately monitor the growth status of cells and ensure that reliable proliferation data is obtained at each time point.

Osteogenic differentiation assessment is achieved by culturing BMSCs in an osteogenic induction medium. Osteogenic induction medium contains high concentrations of β-glycerophosphate, vitamin C, and other ingredients, which can promote the differentiation of BMSCs into osteoblasts. Cells were cultured in an osteogenic induction medium for 3, 6, 9, 12, and 15 days; samples were taken, and the expression of osteogenic-related genes (such as Runx2) was detected by real-time quantitative PCR (qPCR). Runx2 is a key transcription factor in the osteogenesis process that can regulate all stages of bone formation. The qPCR experiment will evaluate the effect of scaffold materials on the osteogenic differentiation ability of BMSCs by analyzing the expression levels of these genes.

4.3. Mechanical properties test

The compression modulus is a quantitative indicator of the elastic properties of a material and is defined as the ratio of stress to strain. In a compression test, the compression modulus is:

$$E_c = \frac{\sigma}{\varepsilon} \tag{7}$$

Stress σ is the ratio of applied force to initial cross-sectional area:

$$\sigma = \frac{F}{A_0} \tag{8}$$

The maximum compressive strength is the maximum compressive stress that the stent material can withstand, which is determined by the extreme point of the material's stress-strain curve in the compression test. The maximum compressive strength formula is:

$$\sigma_{max} = \frac{F_{max}}{A_0} \tag{9}$$

F_{max} loading force before the scaffold material reaches failure, A_0 is the initial cross-sectional area of the stent. The maximum compressive strength is an important parameter for evaluating whether the stent will be damaged or permanently deformed during the stress process.

4.4. Animal experiments and preclinical evaluation

Rabbits were used as experimental animal models in this study because rabbits are of moderate size, have relatively simple bone structures, and their fracture healing process is similar to that of humans. Animal experiments were conducted after obtaining approval from the Ethics Committee to ensure that the experimental process complies with animal welfare standards. A standard bone defect with a diameter of approximately 3 mm was created in the ankle joint area of the rabbit to simulate the bone injury caused by sports injuries. This model can reflect the effects of repair materials on bone defects and is used to evaluate the effect of the new HA/PLA composite scaffold in promoting bone healing.

Animals were regularly evaluated for mobility and functional recovery to evaluate the progress of bone healing. Micro-CT scans were performed 4, 8, 12, and 16 weeks after surgery to observe bone formation in the bone defect area. Micro-CT scans can display changes in bone density, new bone formation, and scaffold degradation with high resolution, providing accurate imaging data for further analysis of the effect of the scaffold. In addition, tissue samples were collected after surgery to further evaluate the regeneration of bone tissue through Masson staining and immunohistochemistry. Masson staining can clearly show the formation of new bone. At the same time, immunohistochemistry can detect the expression of osteogenesis-related markers and quantitatively evaluate the new bone formation rate and scaffold degradation.

In order to further evaluate the actual effect of the scaffold on bone repair, the motor function score was used to evaluate the motor recovery of the animals comprehensively. The motor function score uses a professional scoring scale to comprehensively consider the animal's motor performance (range of motion, load-bearing capacity, pain during exercise, etc.) to provide objective data for functional recovery evaluation.

5. Results

5.1. Biomechanical analysis results

The biomechanical analysis results of the ankle joint under different movements are shown in **Table 1**.

Table 1. Biomechanics of different movements.

Action	Angular velocity (°/s)	Acceleration (m/s^2)	Impact duration (ms)
Land on both feet after jumping	600	5.8	200
Jumping on one foot	720	6.2	220
Quick lateral change of direction	800	7.5	150
Quick spinning kick	950	8.0	180
High altitude landing	950	9.0	210
Quick forward kick	780	6.5	190
Back Kick	730	6.8	200
Quick turn and landing	850	8.2	230

According to the biomechanical data in **Table 1**, the stress conditions of the ankle joint under different martial arts movements show obvious differences. First, in terms of angular velocity, the angular velocities of the movements such as fast rotation kicking and fast rotation landing are relatively high, 950°/s and 850°/s, respectively, which indicates that these movements involve larger joint rotation angles and higher rotation speeds. This high angular velocity usually induces large torsional stress in a short period, causing greater pressure on the ankle joint. In the movements of landing on both feet after jumping and landing on one foot after jumping, the angular velocities are relatively low, 600°/s and 720°/s, respectively, which indicates that these movements have relatively small rotational loads on the ankle joint but still need to withstand the impact force when landing.

The acceleration data further revealed the impact intensity of each action on the ankle joint during execution. Actions such as landing from a high altitude, rapid rotation kicking, and rapid rotation landing have higher accelerations, which are 9.0 m/s^2, 8.0 m/s^2, and 8.2 m/s^2, respectively, indicating that these actions have higher impact forces, especially at the moment of ankle landing or rotation. These instantaneous high accelerations will produce greater stress on the ankle joint, especially at the bone and soft tissue junction, which may increase the risk of injury. In contrast, the accelerations of landing on both feet after jumping and landing on one foot after jumping are 5.8 m/s^2 and 6.2 m/s^2, respectively. Although there are also large impact forces due to the different landing methods, the forces of these actions are relatively dispersed, and the load on the ankle joint is more even.

In terms of impact duration, the impact duration of the rapid lateral change of direction action is short, only 150 ms, which generally indicates that the impact force of the action is generated instantly and dissipated quickly. However, the impact duration of landing with both feet after jumping and landing with one foot after jumping is longer, 200 ms and 220 ms, respectively, which indicates that the impact force after landing lasts longer, which may cause the ankle joint to be in a high-load state for a long time, increasing the possibility of joint injury.

Higher angular velocity and acceleration are usually associated with higher ankle joint loads and potential injury risks, especially in high-intensity movements such as rapid rotation, twisting, and jumping. For these movements, the ankle joint needs to withstand a large force in a very short period and adjust quickly to maintain joint stability. Therefore, reasonable ankle joint training, strengthening muscle strength, and joint stability are crucial to reducing the risk of injury when athletes perform these high-intensity movements.

When landing in different actions, the reaction force is expressed as a multiple of body weight. The results are shown in **Table 2**.

Table 2. Reaction force when landing.

Action	Weight multiples	Variance
Land on both feet after jumping	3.2	0.6
Jumping on one foot	4.0	0.7
Quick lateral change of direction	3.8	0.5
Quick spinning kick	5.1	0.9
High altitude landing	5.3	1
Quick forward kick	3.5	0.4
Back Kick	3.6	0.5
Quick turn and landing	4.2	0.8

According to the data in **Table 2**, we can observe that the landing reaction forces of different martial arts movements show significant differences. The magnitude of the reaction force directly affects the force on the ankle joint and the potential risk of sports injuries. The reaction force of landing with both feet after jumping is 3.2 times the body weight, while the reaction force of landing on one foot after jumping is 4.0

times the body weight. This shows that the reaction force when landing on one foot is greater than when landing on both feet because the single foot bears the entire impact force of landing, while landing on both feet can disperse the impact force to both sides, reducing the burden on each foot. The high reaction force of landing on one foot after jumping may increase the risk of an ankle injury, especially when the athlete does not effectively absorb shock or control the landing action, which may cause excessive load on the ankle joint.

Rapid rotation kicks and high-altitude landings are the most significant, at 5.1 times and 5.3 times body weight, respectively. This high reaction force usually means that the athlete must withstand strong ground impact in a very short time. Since the high-altitude landing falls from a high position, the reaction force under the action of inertia is larger, so its reaction force exceeds that of other actions. Rapid rotation kicks also involve high angular velocity and high acceleration. At the last moment of the kicking action, the contact between the foot and the ground will produce a large reaction force, especially during the rapid rotation process. Considering the reaction forces of these two actions, athletes need to pay special attention to the training of landing techniques and shock absorption ability when performing these high-impact actions to reduce the risk of joint stress and injury.

In rapid lateral changes of direction and rapid rotations, the reaction forces are 3.8 and 4.2 times the body weight, respectively, indicating that lateral changes of direction and rotations have a greater impact on the ankle joint. Lateral changes of direction require the ankle to withstand a large shear force in a short period of time, which poses a challenge to the stability of the ankle joint. At the same time, rotational landings combine rotation and landing impact to create a higher reaction force. Therefore, although these movements do not have extremely high reaction forces like jumping and landing from a high altitude, they also burden the ankle joint more, especially when the reaction speed is insufficient or the movements are not standardized, which can easily lead to injuries.

The reaction forces of fast forward and backward kicks are low, at 3.5 and 3.6 times body weight, respectively. These two movements' reaction forces are smaller than those of jumping or rotating movements because they are more likely to generate strong impact forces through the power output of the leg muscles rather than directly contacting the ground. Although these movements have lower reaction forces, they still require good muscle control and joint stability to ensure that athletes can avoid other types of injuries during execution.

Higher reaction forces are usually accompanied by greater ankle loads, especially in high-impact movements such as rapid rotation, jumping, and landing from high altitudes, which often require stronger joint stability and higher impact resistance. By strengthening leg muscles and improving landing techniques, the impact of reaction forces on the ankle joint can be effectively reduced, thereby reducing the occurrence of sports injuries. In addition, increasing flexibility and agility during training, especially increasing ankle stability training, is essential to improving athletes' performance in these high-impact movements and reducing the risk of injury.

5.2. In vitro cell experiment results

The results of in vitro cell proliferation analysis are shown in **Table 3**.

Table 3. In vitro cell proliferation.

Time (h)	HA/PLA Scaffold	Control group	*P*-value
6	1.02×10^5	0.88×10^5	0.045
12	1.45×10^5	1.25×10^5	0.039
18	1.75×10^5	1.53×10^5	0.032
24	2.02×10^5	1.80×10^5	0.028
30	2.45×10^5	2.10×10^5	0.022
36	2.82×10^5	2.35×10^5	0.018
42	3.10×10^5	2.60×10^5	0.014
48	3.35×10^5	2.80×10^5	0.012

Table 3 shows the proliferation of BMSCs in vitro in the flat culture environment of HA/PLA scaffolds and control groups and includes the *P* value at each time point, which further verifies the significance of HA/PLA scaffolds in promoting cell proliferation. The data show that at all time points (6 h to 48 h), the number of cell proliferations in the HA/PLA scaffold group was significantly higher than that in the control group. Especially in the early stage, the number of cell proliferations in the HA/PLA scaffold group exceeded that in the control group, and this gap gradually widened as the culture time increased. Specifically, at 48 h, the number of cell proliferations in the HA/PLA scaffold group was 3.35×10^5, while that in the control group was 2.80×10^5. The proliferation rate in the HA/PLA scaffold group was higher, and the *P* value between the two groups was less than 0.05 at all time points, indicating that the HA/PLA scaffold has a significant statistical advantage in promoting the proliferation of BMSCs.

The results of the *P* value analysis showed that the cell proliferation advantage of the HA/PLA scaffold group became more obvious over time. Especially in the data after 24 h, the *P* value continued to decline, indicating that the proliferation effect of the HA/PLA scaffold on BMSCs increased with the extension of the culture time. This phenomenon may be related to the role of HA material in the scaffold. The surface properties of HA help to enhance the attachment and expansion of cells, and the degradability of PLA provides an ideal biodegradable environment for cells, allowing cells to proliferate better under the scaffold's support. In contrast, the two-dimensional surface of the flat culture medium limits the growth space and growth mode of cells, resulting in slower cell proliferation.

Osteogenic differentiation is shown in **Table 4**, which shows the expression level of Runx2.

Table 4 compares Runx2 gene expression levels in HA/PLA scaffolds and the control group (flat plate culture) at different osteogenic induction culture days. Runx2 is a key transcription factor in the osteogenic differentiation process, and its expression level directly reflects the degree of BMSCs differentiation into osteoblasts. According to the data, the Runx2 expression in the HA/PLA scaffold group was significantly higher than that in the control group at each time point. As the culture time increased, the Runx2 expression level in the HA/PLA scaffold group gradually increased, showing a strong osteogenic induction effect.

Table 4. Osteogenic differentiation results.

Cultivation days	HA/PLA Scaffold	Control group	*P*-value
3	1.25	0.98	0.041
6	1.68	1.34	0.038
9	2.02	1.62	0.029
12	2.35	1.98	0.021
15	2.58	2.12	0.015

Runx2 expression level in the HA/PLA scaffold group was 1.25, while that in the control group was 0.98, with a *P* value of 0.041, indicating that the HA/PLA scaffold can promote the osteogenic differentiation of BMSCs in a short period. As the culture time increases, the Runx2 expression in the HA/PLA scaffold group gradually increases, reaching 2.58 at 15 days, while that in the control group was only 2.12, with a *P* value of 0.015, indicating that the HA/PLA scaffold has a sustained advantage in promoting the osteogenic differentiation of BMSCs.

From the change in *P* value, the *P* value of all time points was less than 0.05, indicating that the HA/PLA scaffold significantly promoted osteogenic differentiation at each time point. Especially at 12 and 15 days of culture, the expression of Runx2 in the HA/PLA scaffold group was quite different, which further verified the lasting effect of the HA/PLA scaffold on osteogenic differentiation. In contrast, due to the scaffold's lack of three-dimensional structural support, the differentiation rate of BMSCs in the control group was slower, and the expression level of Runx2 was always lower than that of the scaffold group. The HA/PLA scaffold significantly promoted the osteogenic differentiation of BMSCs through its bioactivity and structural properties, especially during long-term culture; the scaffold's induction effect on osteogenesis was more significant. This result shows that the potential of HA/PLA scaffolds as bone repair materials in bone tissue engineering can effectively accelerate bone healing and improve the repair effect.

The mechanical properties test results are shown in **Table 5**, which shows the maximum compressive strength.

Table 5. Mechanical properties test.

Cultivation days	HA/PLA Scaffold	Control group	*P*-value
3	3.8 MPa	3.2 MPa	0.045
6	4.2 MPa	3.6 MPa	0.038
9	5.0 MPa	4.3 MPa	0.031
12	5.5 MPa	4.6 MPa	0.022
15	6.0 MPa	5.0 MPa	0.018

Table 5 presents a comparison of the maximum compressive strength of the HA/PLA scaffold and the control group (flat plate culture) under different osteogenic induction culture durations. The data reveal that the HA/PLA scaffold group

consistently exhibits significantly higher compressive strength than the control group at each time point. Additionally, as the culture time increases, the compressive strength of the HA/PLA scaffold group continues to rise, demonstrating a clear advantage in mechanical properties. At day 3, the maximum compressive strength of the HA/PLA scaffold group was 3.8 MPa, significantly higher than the 3.2 MPa observed in the control group (P = 0.045). As the culture time progresses, the scaffold group's compressive strength gradually increases, reaching 6.0 MPa at 15 days, compared to 5.0 MPa in the control group, with the difference becoming even more significant (P = 0.018).

These results indicate that the HA/PLA scaffold not only supports osteogenic differentiation during bone repair but also enhances the mechanical strength of the repair area, contributing to the overall stability of the bone tissue. In contrast to the flat plate culture used in the control group, the three-dimensional structure of the HA/PLA scaffold offers better support and stress distribution. This structural advantage allows the scaffold's mechanical strength to improve over time during the osteogenesis process, with particularly notable performance in long-term culture. The control group's low compressive strength can likely be attributed to the lack of three-dimensional structural support, which limits cell growth and mineralization, thereby hindering the development of higher compressive strength. In summary, the HA/PLA scaffold demonstrates significant advantages in promoting cell proliferation, osteogenic differentiation, and enhancing the mechanical strength of the bone healing area. As the compressive strength continues to improve over time, the HA/PLA scaffold shows promising potential as a bone repair material, particularly for applications involving long-term loads and high-intensity impacts.

5.3. Animal experiment results

Micro-CT scanning showed that the results of the bone density analysis were shown in **Figure 2**.

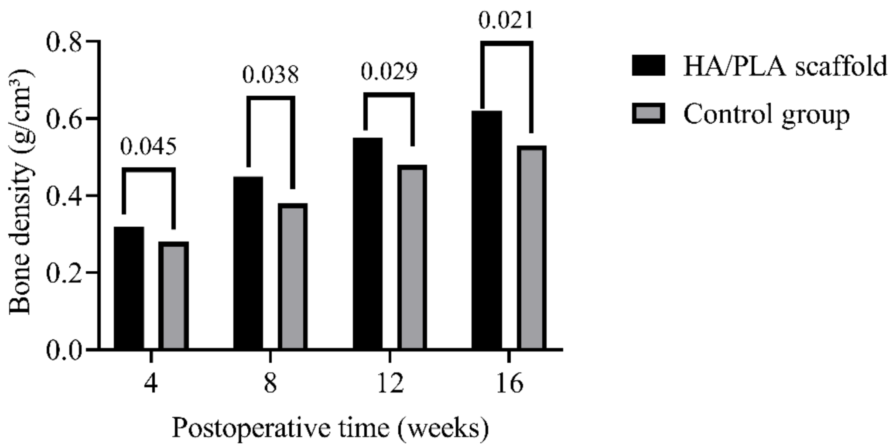

Figure 2. Bone density results.

According to the micro-CT scan data in **Figure 2**, the bone density values of the HA/PLA scaffold group at different time points after surgery were higher than those of the control group, and the bone density of the HA/PLA scaffold group gradually increased over time. Four weeks after surgery, the bone density of the HA/PLA scaffold group was 0.32 g/cm^3, which was statistically significant compared with 0.28 g/cm^3 in the control group (P = 0.045), indicating that the HA/PLA scaffold can promote the improvement of bone density in the early stage. As time went on, at 8 weeks, 12 weeks, and 16 weeks after surgery, the bone density values of the HA/PLA scaffold group were 0.45 g/cm^3, 0.55 g/cm^3, and 0.62 g/cm^3, respectively, while those of the control group were 0.38 g/cm^3, 0.48 g/cm^3, and 0.53 g/cm^3, respectively. The HA/PLA scaffold group always showed a significant advantage, and the P value continued to be less than 0.05, indicating that this difference was statistically significant. The increased bone density of HA/PLA scaffolds reflects their effectiveness in the bone repair process. The biocompatibility and bioactivity of the scaffold material promote the formation of new bone. As the main component of the scaffold, HA material can simulate the structure and function of natural bone minerals, promote the attachment, proliferation, and differentiation of bone cells, and further accelerate the bone healing process. In addition, the degradability of PLA provides an ideal bone repair environment. As the material gradually degrades, new bone can gradually replace the scaffold to form a stable bone structure.

In contrast, the bone density of the control group cultured on flat plates increased slowly. The bone density (0.53 g/cm^3) at 16 weeks after surgery was still lower than that of the HA/PLA scaffold group (0.62 g/cm^3), indicating that flat plate culture has a limited effect in promoting bone healing. The scaffold's lack of three-dimensional structural support limits the formation and mineralization of new bone. The HA/PLA scaffold shows advantages in promoting BMSCs proliferation and osteogenic differentiation, effectively improves bone density in the bone repair area, and has good application prospects. This result strongly supports the clinical application of HA/PLA scaffolds as bone repair materials.

The compatibility of new bone with host bone tissue was analyzed based on the results of Masson staining, and the results are shown in **Figure 3**.

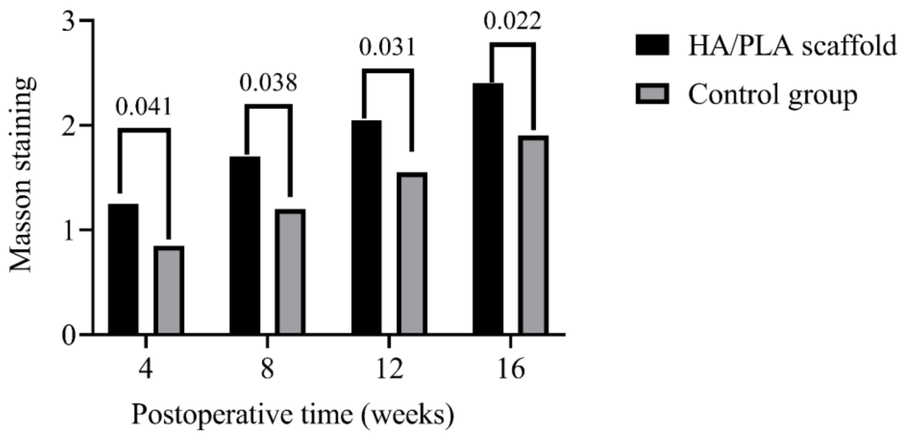

Figure 3. Compatibility analysis.

Figure 3 shows the analysis of the compatibility of new bone and host bone tissue in the Masson staining results of the HA/PLA scaffold group and the control group at different time points after surgery. Masson staining is mainly used to evaluate the combination of new bone and host bone. The bone matrix is displayed by blue staining, and the degree of mineralization of new bone is indicated by green. According to the data, the new bone formation and mineralization of the HA/PLA scaffold group at each time point were significantly better than those of the control group. As time went on, the combination of new bone and host bone in the scaffold group gradually increased, and the degradation process of the scaffold material matched the recovery of bone tissue. At 4 weeks after surgery, the Masson staining result of the HA/PLA scaffold group was 1.25, which was significantly higher than 0.85 of the control group, with a *P* value of 0.041, indicating that the formation of new bone and the combination with host bone showed significant differences in the early stage. By 8 weeks after surgery, the new bone formation in the HA/PLA scaffold group increased further, with a staining result of 1.70, while that in the control group was only 1.20, with a *P* value of 0.038, indicating that the HA/PLA scaffold not only promoted the formation of new bone but also enhanced the combination of new bone and host bone. As time went on, at 12 and 16 weeks after surgery, the results of the HA/PLA scaffold group were 2.05 and 2.40, respectively, while those of the control group were 1.55 and 1.90. The *P* value continued to be less than 0.05, indicating that the role of HA/PLA scaffolds in bone repair continued to increase.

The advantages of HA/PLA scaffolds may come from the three-dimensional design of their scaffold structure. HA's biocompatibility and mineralization-promoting properties enable new bone to be generated quickly under the support of the scaffold structure and gradually replace the degrading scaffold material to restore the normal bone structure in the bone defect area. The degradability of PLA enables the scaffold material to be gradually replaced by new bone without interfering with bone healing, thereby avoiding the adverse effects of long-term materials in the body on bone healing. In contrast, the control group relied only on plate culture and failed to provide three-dimensional support similar to the scaffold, resulting in a loose combination of new bone and host bone and a slow rate of new bone formation. HA/PLA scaffolds have significant advantages in promoting new bone formation and enhancing the combination of new bone and host bone by providing an ideal support structure. As the scaffold material gradually degrades, the new bone can gradually occupy the space of the scaffold and restore the function of the bone defect area, which provides a solid theoretical basis and experimental data support for its application in the field of bone repair.

6. Conclusion

Remarkable results by conducting an in-depth exploration of the application of HA/PLA composite scaffolds in bone repair. HA/PLA scaffolds can effectively promote the proliferation and osteogenic differentiation of BMSCs and show significant proliferation advantages and strong osteogenic induction ability in vitro experiments. Secondly, the experimental results of micro-CT scanning and Masson staining show that HA/PLA scaffolds have good effects in promoting new bone formation, improving bone density, and enhancing the compatibility of new bone with host bone. The degradation process of the scaffold material is consistent with the bone repair process. The results of the mechanical properties test show that HA/PLA scaffolds can significantly improve the compressive strength of the bone defect area and have good mechanical support capacity. The contribution of this study is to provide a new type of bone repair material, HA/PLA composite scaffold, which breaks through the limitations of traditional bone repair methods, has good biocompatibility, mechanical properties, and bone promotion ability, and provides a new solution for bone tissue engineering. It has broad application prospects in sports injury repair and fracture healing and has important practical significance for clinical bone repair treatment.

However, the study also has certain limitations, such as the small sample size of animal experiments, and the evaluation of long-term effects still needs further verification. In addition, this study mainly focused on the bioactivity and mechanical properties of the material. In the future, it is necessary to explore its application effects in more complex environments and possible biosafety issues. Future research should further expand the application of HA/PLA scaffolds in clinical bone repair, explore the effects of different material component ratios on bone repair, and conduct larger-scale preclinical and clinical trials to verify its long-term bone repair effect and biosafety. In addition, other advanced technologies, such as drug release systems, antibacterial functions, etc., can be combined further to enhance the versatility and therapeutic effects of the scaffold.

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Conflict of interest: The author declares no conflict of interest.

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