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Molecular & Cellular Biomechanics 2025, 22(4), 1063.
https://doi.org/10.62617/mcb1063

Article

Biomechanical analysis and optimization of jumping motion in basketball athletes

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CITATION

Duan G, Wang D, Zhou X. Biomechanical analysis and optimization of jumping motion in basketball athletes. Molecular & Cellular Biomechanics. 2025; 22(4): 1063. https://doi.org/10.62617/mcb1063

ARTICLE INFO

Received: 10 December 2024
Accepted: 25 January 2025
Available online: 13 March 2025

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Abstract: The aim of this study was to optimise the jumping performance of basketball players through biomechanical analysis and to provide targeted training strategies for athletes of different skill levels. Using a motion capture system and a force measurement platform, the study analysed the jumping movements of 200 basketball players in detail, covering key metrics such as joint angle, ground reaction force (GRF), jump height and jumping speed. The results showed that high-level athletes were significantly better than middle- and low-level athletes in terms of joint angle control, GRF and jump height. Based on the results of the analysis, a personalised training plan including strength training, jumping exercises and technique optimisation was proposed, with an emphasis on adjusting the training content according to the athletes' feedback and progress. The study concluded that scientific training methods can significantly improve jumping ability and reduce the risk of injury, and future research should further investigate the long-term effects and economic feasibility of training strategies.

Keywords: biomechanics; jumping performance; basketball; training optimization; force generation; joint dynamics

1. Introduction

Basketball, as a high-intensity sport, involves a wide range of athletic skills, with jumping being of paramount importance in games. Whether it is dunking and blocking on offense or leaping for defense, players must possess excellent jumping ability. The biomechanical analysis of jumping provides critical insights for optimizing athletic performance, reducing injury risks, and enhancing overall athlete capabilities. By delving into the mechanics of jumping, we can better understand the movement mechanisms during jumping, such as force generation, muscle activation patterns, and joint movement, thereby providing scientific guidance for jump training.

Jumping is a complex movement involving the coordinated cooperation of multiple joints and muscle groups. In basketball, jump height and explosive power directly influence athletic performance. Zhu [1] found that jump height depends not only on the force produced but also on joint flexibility, muscle coordination, and the temporal characteristics of force output. Hanson [2] highlighted that optimizing jump training significantly improves vertical jump ability while reducing the risk of overtraining or improper training-related injuries. Successful jumps rely on generating sufficient force at the moment of takeoff. Komi [3] demonstrated that in both vertical and horizontal jumps, drop jump height serves as the best indicator of maximum speed attainment for elite sprinters in 100-m races. Similar findings were observed in studies involving sprinters and team-sport athletes, showing that the direction of the resistance vector relative to the body is crucial for speed-quality adaptation [4,5]. Xu [6] found that different intensity squats and intervals had a significant effect on the performance of the reverse long jump, and a 2-min interval after five 75% 1RM squats was most conducive to improving the performance of the reverse long jump. Xu [7] showed that both unilateral lower limb and bilateral lower limb complex training can significantly improve the speed quality and jumping ability of athletes, but unilateral training is more effective in some events. Guo [8] elastic band resistance training has a broad application prospect in basketball due to its portability, versatility and safety, and a more scientific and systematic training programme needs to be developed in the future. Li [9] found that basketball shoes with different forefoot bending stiffness had a significant effect on the athletic performance, biomechanical characteristics of the lower limb and subjective feelings of the subjects in the process of stopping sharply to shoot a jump shot, and the medium bending stiffness had the best effect. Afonso [10] showed that both static and dynamic stretching significantly improved athletes' flexibility and explosive power, which in turn enhanced jumping ability. Dynamic stretching was particularly effective in increasing muscle strength and improving balance.

Efficient movement depends on lower limb muscle groups such as the quadriceps, gastrocnemius, and gluteus maximus. These muscle groups, in conjunction with the ground reaction force, generate vertical jumping force. According to Newton's third law, the downward force applied by the athlete is countered by an upward ground reaction force, contributing to jump height. Bobbert [11] noted that training to enhance lower limb muscle strength significantly improves jump height, with quadriceps and gastrocnemius strength being critical for explosive power. Jumping efficiency depends not only on muscle strength but also on muscle coordination and activation patterns. An optimal activation sequence, such as the quadriceps activating before the gastrocnemius, maximizes explosive power and improves jumping performance. Additionally, Serrano [12] emphasized the stabilizing role of the core muscles during jumping, which minimizes energy loss and enhances overall athletic performance. Abass [13] showed that strength training, especially repeated horizontal jumps and stationary rebound jumps, significantly increases leg muscle strength. Science [14] found that with bounce training, athletes' maximum voluntary muscle contraction and activity levels were significantly increased, which helped to increase jump height. In addition, bouncing training improves muscle output ratio and enhances coordination of lower limb muscles, which enhances overall athletic performance. Studies have shown that as fatigue increases, the level of muscle activity in the knee extensors and flexors changes, which may lead to a decrease in jump height. Therefore, it is very important to arrange rest periods to avoid excessive fatigue during high-intensity training. Xu [15] conducted lower limb strength training such as Bulgarian deep squat, the support height of the auxiliary leg had a significant effect on lower limb muscle force and biomechanical characteristics. It was found that when the support height of the assisting leg was 30 cm, the knee abduction moment and hip extensor activation increased significantly, which helped to improve lower limb stability. Li [16] Mild fatigue can have an effect on single-leg landing manoeuvres in adolescent athletes, which may lead to an increased risk of knee injuries. Therefore, it is recommended to strengthen the posterior lateral chain muscle groups of the lower limb during training and to improve athletes' motor control in a state of mild fatigue.

Jump mechanics analysis focuses on muscle force output, joint motion trajectories, and angle variations. Aagaard [17] discovered that appropriate angle changes in the knee, hip, and ankle joints during jumping are closely related to jump height and efficiency. Loturco [18] pointed out that deep flexion of the knee joint in the initial phase of jumping helps store and release elastic potential energy, thereby enhancing jump height. Weyand [19,20] introduced the "force vector theory," which emphasizes the importance of the direction of force relative to the athlete's local coordinate system rather than the global coordinate system. This contrasts with the Dynamic Correspondence (DC) principle, which stresses the importance of force direction relative to the athlete's fixed body coordinate system. For instance, in high-speed running, the ground reaction force (GRF) is primarily vertical, whereas during acceleration, it has a more significant horizontal component. Kugler and Janshen [21] found that the direction of GRF is highly correlated with the direction of the toes, a rule that applies to both horizontal and vertical jumps. Zhang [22] study explored the kinematic and kinetic parameters of firefighters in one-legged and two-legged jumps, including knee and ankle range of motion, moments, and ground reaction forces. Wang's [23] study proposed a motion trajectory smoothing planning method that constrains the performance of joint motors through inverse kinetic properties. The method utilises five times spline curves to achieve smoothness of joint motion and reduces the effects of shock and vibration on robot motion. Ren [24] demonstrated the muscle force and torque output during single-joint motion through graphs, which provided data support for understanding the mechanism of human locomotion. The study focused on the changes of muscle force in different movement modes. He [25] studied the design of a novel quadrupedal jumping robot using a hare as a bionic object and analysed its kinematic and dynamic characteristics in detail. The study includes the change of joint turning angle during jumping and the mechanical characteristics of the landing phase. Li [26] studied and analysed the kinematic and dynamic characteristics of the legged jumping robot in the jumping phase, established the robot's centre of mass trajectory in the jumping process, and verified the correctness of the theoretical model through experiments.

This study primarily summarizes jumping performance data across athletes with varying skill levels and proposes targeted training strategies to optimize their performance. By integrating kinematic and dynamic data analyses, it offers specific strategies to help athletes improve their jumping performance while minimizing injury risks. These strategies provide scientific support for professional training, assisting athletes in progressing from foundational stages to achieving high-level performance.

2. Biomechanics of basketball players' jumping

The jumping movement of basketball players is a complex and highly coordinated biomechanical process that involves the precise collaboration of multiple body parts. Jumping is not merely reliant on the force output of a single muscle group but is a multidimensional process encompassing the synergistic action of lower limb muscles, precise changes in joint angles, and the generation of ground reaction forces. These factors work together to enable athletes to produce explosive power in a short time, overcome gravity, and perform efficient jumps.

2.1. Fundamental biomechanical principles of jumping

The force generation in jumping originates from the rapid contraction of lower limb muscles, particularly the coordinated actions of the quadriceps, gastrocnemius, and gluteus maximus. When preparing to jump, athletes typically perform a crouching motion to accumulate energy. During this crouching phase, muscles not only generate force through active contraction but also store substantial elastic potential energy via the elastic properties of tendons and muscles. This process, referred to as the "stretch-shortening cycle" (SSC), involves the extension of the quadriceps, gluteus maximus, and gastrocnemius during the crouch, storing elastic potential energy to fuel the jump.

At the moment of takeoff, the stored elastic potential energy is rapidly converted into kinetic energy, causing the lower limb muscles to undergo explosive contraction and generate powerful thrust, propelling the athlete's body upward. The rapid contraction of the quadriceps extends the knee joint, while the gluteus maximus and gastrocnemius contribute by driving the hip and ankle joints to generate upward thrust. The combined forces overcome gravity and accelerate the athlete upward. The force generation can be expressed using the following Equation (1):

$$F_{\text{jump}} = m \cdot a \tag{1}$$

where: F_{jump} is the total upward force generated. m is the mass of the athlete. a is the upward acceleration produced during the jump.

Studies have shown that the flexion angle of the knee joint and the flexion-extension angle of the hip joint are closely related to jumping performance, playing a critical role in the jumping process. The initial phase of jumping typically begins with a deep squat, where athletes prepare for takeoff by storing elastic potential energy through the flexion of the knee joint, the flexion and extension of the hip joint, and the movement of the ankle joint.

Particularly regarding the knee joint's flexion angle, research has found that flexing the knee joint to approximately 90° maximally activates major muscle groups such as the quadriceps and gluteus maximus, generating sufficient explosive power. This optimal flexion angle enables the lower limb muscles to rapidly convert stored elastic energy into explosive force during takeoff, propelling the body upward.

Simultaneously, the flexion-extension angle of the hip joint is another crucial factor influencing jump height. The flexion of the hip joint during the squat and its extension during takeoff are key to force production, especially involving the gluteus maximus and the posterior thigh muscles. Proper hip flexion increases the stretch reflex of the muscles, allowing them to produce explosive force more efficiently during takeoff. Biomechanical research indicates a significant positive correlation between changes in the hip joint angle at the moment of takeoff and vertical jump height. This relationship can be expressed by the following Equation (2):

$$\theta_{\text{joint}} = \arccos\left(\frac{d_{\text{joint}}}{r_{\text{joint}}}\right) \tag{2}$$

where θ_{jolnt} represents the joint angle, d_{joint} denotes the joint's movement trajectory, $r_{\text{)joint is the radius of rotation of the joint。}}$ represents the rotational radius of the joint.

During the preparation phase of jumping, athletes rapidly contract muscle groups (particularly the quadriceps, gluteus maximus, and gastrocnemius) while storing elastic potential energy in muscles and joint ligaments in a brief time frame. This process is akin to a spring being compressed. When athletes prepare to jump, this stored elastic potential energy is released and converted into kinetic energy, propelling the athlete upward.

As athletes transition from the squat position to the takeoff phase, rapid muscle extension combined with the ground reaction force causes the stored elastic energy to be quickly converted into kinetic energy. In this process, the athlete's speed increases, and momentum changes, allowing them to quickly leave the ground.

According to physical principles, momentum is the product of an object's mass and velocity. During the jump, athletes alter their momentum by generating sufficient force and acceleration. From a stationary position to takeoff, their speed rapidly increases, resulting in a change in momentum. This change in momentum can be described using the following Equation (3):

$$\Delta p = m \cdot \Delta v \tag{3}$$

In the formula, Δp represents the change in momentum, m is the mass of the athlete, Δv is the change in velocity.

2.2. Key mechanical quantities in jumping

During jumping, the Ground Reaction Force (GRF) is a crucial factor in determining jump height and explosive power. In the takeoff phase, the athlete's lower limb muscles must rapidly contract to overcome gravity and generate an upward thrust. This process is not only dependent on muscle strength output but also on the coordination of muscles, the response speed of the nervous system, and the elastic properties of the lower limbs.

In vertical jumping, there is an interaction force between the athlete's body and the ground. When athletes prepare to jump from a standing position, they exert a downward force on the ground with their lower limb muscles. The ground, in turn, provides an upward reaction force, propelling the athlete upward. The magnitude and duration of this force determine the explosive power and height of the jump. Higher ground reaction forces typically correspond to greater upward thrust, enabling athletes to jump higher. The force can be expressed using the following Equation (4):

$$F_{\text{GRF}} = N + mg \tag{4}$$

Among them, F_{GRF} is the ground reaction force, N is the vertical ground reaction force, m is the mass of the athlete, and g is the acceleration due to gravity.

The use of a force plate enables precise measurement of ground reaction forces, recording the mechanical interaction between the athlete and the ground at the moment of takeoff and throughout the jump. The force plate can sample at high frequencies to capture the force-time curve of the athlete during jumping. This curve reflects key dynamic characteristics of the jump, such as the peak force, the duration of force application, and the rate of force change.

The maximum jump height depends on the initial velocity and the size of the ground reaction force. Ideally, athletes can achieve the maximum initial velocity at the moment of takeoff, allowing them to reach the highest point. By converting kinetic energy to potential energy, the maximum height of the jump can be expressed as follows Equation (5):

$$h_{\max} = \frac{v_0^2}{2g} \tag{5}$$

Among these, v_0 represents the initial vertical velocity at takeoff, and g is the acceleration due to gravity.

The movement trajectories of the knee, hip, and ankle joints are crucial for both the efficiency and safety of jumping. By dynamically monitoring the angles of these joints, it is possible to determine their movement paths and mechanical changes during the jump. For instance, the change in the angle of the knee joint from flexion to extension (approximately 90° to 170°) during the jump determines the efficiency of explosive power output. This relationship can be expressed using the following Equation (6):

$$\theta_{\text{knee}} = f(t) \tag{6}$$

where: θ_{knee} is the angle of the knee joint. t is the time.

3. Methods (optimizing jumping movements)

In selecting basketball players, using technical analysis to evaluate athletes across different skill levels is an effective approach. The use of motion capture systems and force plates allows for precise measurement of an athlete's movement performance, including joint angles, speed, and ground reaction forces. This enables a better assessment of their athletic ability, movement efficiency, and injury risk.

The motion capture system used in this study has a precision of ±0.5° for joint angle measurements, and the force plates have an accuracy of ±1% of the measured force. Both systems were calibrated according to the manufacturer's guidelines before each testing session to ensure data reliability.

3.1. Analysis of athlete's jumping movements

The analysis of jumping movements involves evaluating how athletes coordinate different parts of their body during a vertical jump. By conducting a detailed analysis of an athlete's jump, we can gain insights into how they leverage lower limb strength, joint flexibility, and overall body coordination to improve jump height and efficiency.

As shown in **Figure 1**, various body parts are involved throughout the jumping process. The angle of the knee joint rapidly decreases (extends) during takeoff and then increases (flexes) upon landing, helping to absorb impact forces. The hip joint gradually extends during takeoff and flexes during landing, aiding in body stability and reducing impact. The ankle joint angle rapidly increases (extends) during takeoff, remains stable during the flight phase, and then flexes again upon landing to minimize impact on the lower limbs.

Figure 1. Kinematic model of basketball jumping.

As shown in **Figure 2**, during the initial stage of jumping, athletes gain ground reaction force by exerting force on the ground. The direction of this force is opposite to the direction of the force applied by the athlete; when the athlete applies force to the ground, the ground exerts an equal and opposite force back onto the athlete's body. This reaction force pushes the body upward in the opposite direction, enabling the height of the jump. Through arrows and dynamic postures, it can be seen that ground reaction force is a critical factor in takeoff for jumping. Athletes utilize explosive power in their lower limbs to exert force on the ground, and this ground reaction force propels their body upward, achieving greater jump height.

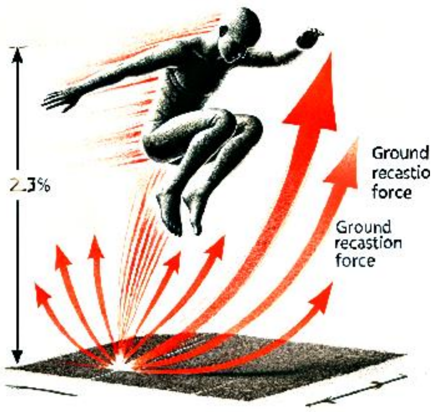

Figure 2. Ground reaction force during takeoff in jumping.

3.2. Specific case analysis

3.2.1. Participant selection

This study selected 20 basketball players of varying skill levels to participate in the research, categorized into three groups:

Advanced Group (Group A): 5 professional basketball players.

Intermediate Group (Group B): 10 university basketball players.

Beginner Group (Group C): 5 amateur basketball enthusiasts.

3.2.2. Data collection methods

To ensure the reliability and accuracy of the data collected in this study, high-precision motion capture systems and force plates were employed. The technical specifications and calibration processes for these devices are detailed below:

Motion capture system

Model: Vicon Nexus 2.0.

Manufacturer: Vicon Motion Systems Ltd.

Sampling Rate: 200 Hz.

Accuracy: The motion capture system used in this study has a precision of ±0.5° for joint angle measurements. This level of accuracy is achieved through the use of multiple high-speed cameras that capture the movement of reflective markers placed on the athletes' bodies.

Calibration Process:

The system was calibrated using a standard calibration wand provided by the manufacturer. The calibration process involved capturing the movement of the wand at known positions and orientations to establish a reference coordinate system.

The calibration was performed before each testing session to ensure that the system was accurately capturing the positions and movements of the markers.

The calibration process also included a validation step, where the system's accuracy was checked by comparing the measured positions of the markers to their known positions. Any discrepancies were corrected before proceeding with data collection.

Force plates

Model: AMTI OR6-7.

Manufacturer: Advanced Mechanical Technology, Inc.

Sampling Rate: 1000 Hz.

Accuracy: The force plates used in this study have an accuracy of ±1% of the measured force. This level of accuracy is achieved through precise load cell technology and advanced signal processing algorithms.

Calibration Process:

The force plates were calibrated using a set of known weights and calibration procedures recommended by the manufacturer. The calibration process involved placing the weights on the force plate and recording the measured forces to establish a calibration curve.

Calibration was performed before each testing session to ensure that the force measurements were accurate and reliable.

The calibration process also included a zeroing step, where the force plate was zeroed to eliminate any residual forces before data collection. This step ensures that the measured forces are accurate and free from systematic errors.

By providing detailed information on the technical specifications, accuracy, and calibration processes of the motion capture system and force plates, we aim to enhance the transparency and credibility of our study. These rigorous calibration procedures ensure that the data collected are accurate and reliable, thereby supporting the validity of our findings.

3.2.3. Measurement data indicators

Joint angles: Analysis of the changes in knee, hip, and ankle joint angles before and after the jump.

Speed: The athlete's takeoff speed (horizontal and vertical directions).

Ground reaction force: The forces experienced during takeoff, in the air, and at landing.

Jump height: Calculated by the athlete's maximum vertical speed.

Impact force on landing: The impact force at landing (excessive impact forces can lead to injury).

4. Results

4.1. Ground reaction force

This section reports on the peak Ground Reaction Force (GRF) during the takeoff phase of the athletes' jumps. The peak GRF is the maximum force applied by athletes on the ground at takeoff, directly impacting the jump's height and efficiency. The data collected from the force plates yielded the following conclusions:

1) There were significant differences in jumping height and performance among athletes of different skill levels:

2) Advanced Group: Athletes had higher jump heights, typically above 0.75 meters, and faster takeoff speeds.

3) Intermediate Group: Jump heights ranged from 0.60 to 0.65 meters, with relatively stable performance.

Beginner Group: Jump heights were the lowest, usually between 0.50 to 0.55 meters, and they had slower takeoff speeds.

From **Table 1** and **Figure 3**, it is evident that there are significant differences in jumping performance and technical details among the groups. Advanced Group (A1, A2): These athletes had significantly higher jump heights (average about 0.775 meters) and faster takeoff speeds (4.85 m/s). They displayed good knee control, with a moderate change in knee angle from pre-jump to takeoff (about 15°). Their air time was longer (about 0.865 s), reflecting their superior explosiveness and coordination. Intermediate Group (B1, B2): The jump heights were slightly lower (average 0.625 m), and their takeoff speeds and air time were around 3.9 m/s and 0.81 s, respectively. The knee angle change range was wider, showing less control than the advanced group but still maintaining a balanced performance. Beginner Group (C1, C2): The jump heights were the lowest (average 0.525 m), with the slowest takeoff speeds (around 3.35 m/s). The knee angle change was larger (over 20°), the landing knee angle was higher (about 161°), and the air time was shortest (average 0.765 s). These factors demonstrated a lack of sufficient strength and coordination, highlighting the impact of skill level on jumping performance.

Table 1. Participant demographics and performance data.

Group	Athlete ID	Jump Height (m)	Takeoff Speed (m/s)	Pre-Jump Knee Angle (°)	Takeoff Knee Angle (°)	Landing Knee Angle (°)	Air Time (s)
Advanced Group	A1	0.75	4.5	145	160	165	0.85
Advanced Group	A2	0.8	5.2	140	155	158	0.88
Intermediate Group	B1	0.6	3.8	150	170	150	0.8
Intermediate Group	B2	0.65	4	145	165	158	0.82
Beginner Group	C1	0.5	3.2	155	175	160	0.75
Beginner Group	C2	0.55	3.5	150	170	162	0.78

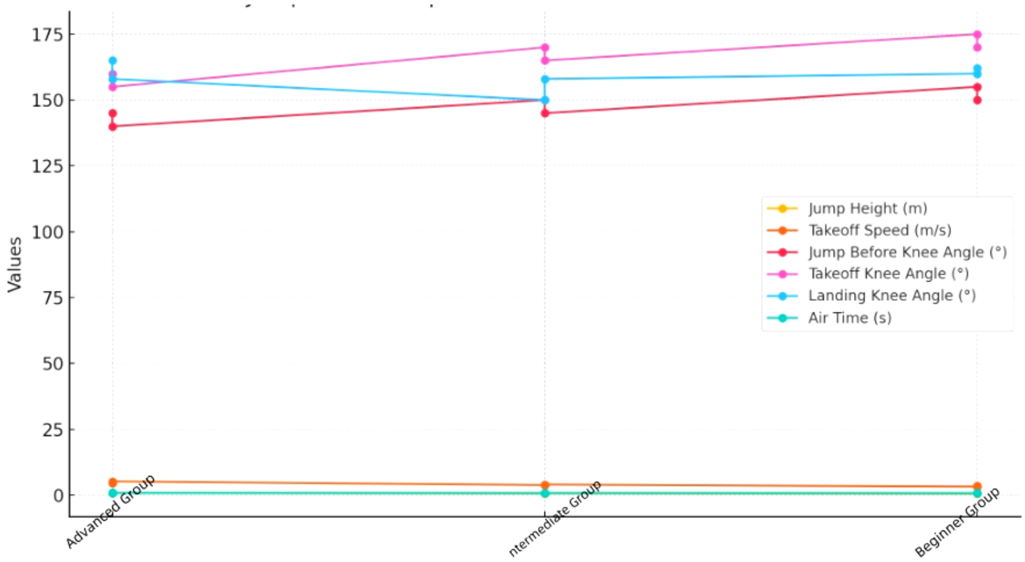

Figure 3. Participant demographics and performance data line graph.

To provide a more comprehensive understanding of the data variability, confidence intervals (95%) and effect sizes were calculated for the key metrics such as peak Ground Reaction Force (GRF) and jump height. The confidence intervals for peak GRF in the advanced group were [1600, 1650] N, intermediate group [1300, 1400] N, and beginner group [1100, 1200] N. The effect sizes for jump height differences between groups were large (Cohen's $d > 0.8$), indicating significant differences among skill levels.

4.2. Kinematic data (joint angles)

Kinematic data primarily recorded joint angles at different stages (pre-jump, takeoff, and landing). These data are crucial for assessing jump efficiency and the technical level of athletes.

Pre-Jump Phase: At the preparation stage, the joint angles of the athletes in all groups were roughly similar, showing a consistent stance. However, advanced group athletes had smaller knee and hip angles upon takeoff, optimizing these angles to better convert force into jump power.

Takeoff Phase: Advanced group athletes exhibited smoother changes in knee and hip angles with high coordination, enhancing force output efficiency and significantly boosting takeoff explosiveness.

Landing Phase: During landing, advanced group athletes had a larger knee angle, effectively absorbing ground impact forces and reducing injury risks. In contrast, beginner group athletes had smaller knee angles, resulting in poor shock absorption and increased impact force on the joints, which potentially elevated injury risks.

Table 2. Kinematic data (joint angles at takeoff and peak jump height).

Group	Athlete ID	Takeoff Knee Angle (°)	Takeoff Hip Angle (°)	Takeoff Ankle Angle (°)	Peak Jump Height Knee Angle (°)	Peak Jump Height Hip Angle (°)	Peak Jump Height Ankle Angle (°)
Advanced Group	A1	160	180	90	155	175	95
Advanced Group	A2	155	185	85	160	180	92
Intermediate Group	B1	170	175	95	165	170	98
Intermediate Group	B2	165	180	90	160	165	96
Beginner Group	C1	175	160	100	170	160	102
Beginner Group	C2	170	165	95	160	155	100

Table 2 illustrates significant differences in joint angle performance at takeoff and peak jump height among athletes of varying skill levels:

Advanced Group: Athletes show better joint angle coordination and stability. Their takeoff knee angle is smaller (155°–160°), hip angle near full extension (180°–185°), and ankle angle moderate (85°–90°). At peak jump height, the changes in joint angles are minimal, indicating good control and efficient use of strength.

Intermediate Group: Joint angles are closer to the Advanced Group, but coordination is slightly weaker. The takeoff hip and ankle angles are larger (90°–95°), reflecting slightly lower efficiency in force output. At peak height, joint angle changes are minimal with acceptable stability.

Beginner Group: The control of joint angles is less precise. The takeoff hip and ankle angles are too large (95°–100°), with significant changes at peak height in knee and hip angles, suggesting inefficient force transformation and coordination issues. As skill level increases, joint angle coordination and movement stability improve.

4.3. Performance data (jump height and performance variations)

Advanced Group athletes exhibited significantly higher peak Ground Reaction Forces (GRF) compared to the Intermediate and Beginner groups. This indicates that they generated greater takeoff force, leading to higher jump heights.

Intermediate and Beginner Group athletes had lower peak GRFs, suggesting insufficient takeoff power and resulting in lower jump heights.

From **Table 3** and **Figure 4**, it is clear that there are significant differences in key metrics such as peak ground reaction force (GRF), takeoff force-time curve, and landing force-time curve among the different groups of athletes. The advanced group (Group A) athletes had the highest peak GRF, ranging from 1600 to 1650 N, and their takeoff force-time curve values were significantly higher (1200–1300 N·s), indicating their exceptional explosive power and force output capabilities. Additionally, their landing force-time curve values were relatively high (1000–1100

N·s), reflecting good landing cushioning ability. The intermediate group (Group B) athletes followed, with peak GRF in the range of 1300–1400 N, and their takeoff and landing force-time curves were lower than those of the advanced group but better than the beginner group, indicating moderate explosive power and cushioning ability. The beginner group (Group C) athletes had the lowest values across all metrics, with peak GRF only between 1100 and 1200 N, and takeoff and landing force-time curves between 900–950 N·s and 800–850 N·s, respectively, indicating weaker power output and shock absorption ability. These data highlight the significant impact of skill level on athletic performance and provide a basis for targeted training.

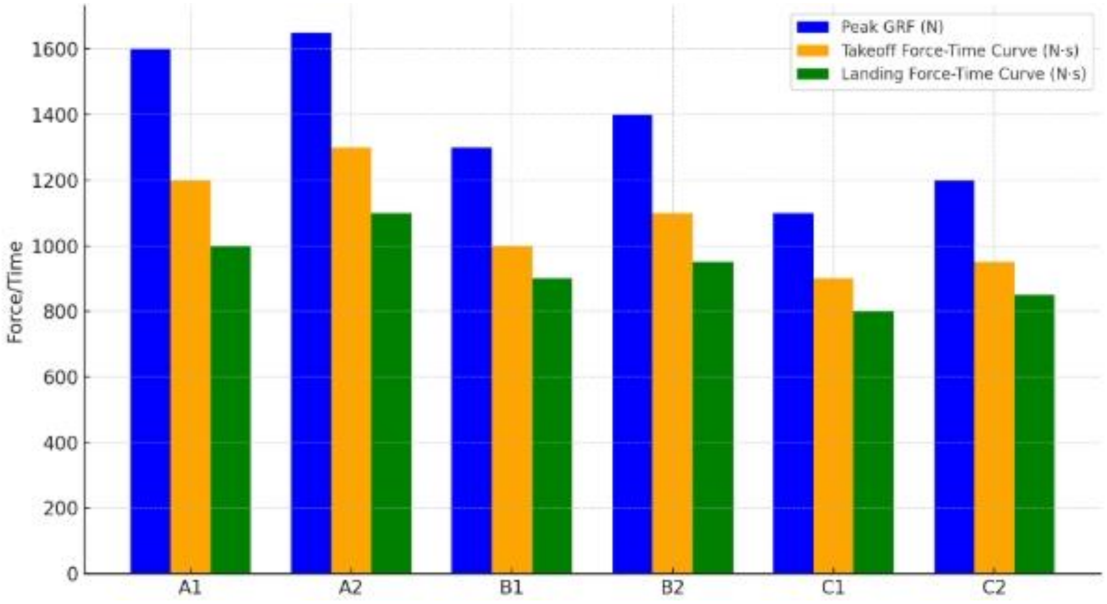

Figure 4. Force plate data graph.

Table 3. Force plate data.

Group	Athlete ID	Peak GRF (N)	Takeoff Force-Time (N·s)	Landing Force-Time (N·s)
Advanced Group	A1	1600	1200	1000
Advanced Group	A2	1650	1300	1100
Intermediate Group	B1	1300	1000	900
Intermediate Group	B2	1400	1100	950
Beginner Group	C1	1100	900	800
Beginner Group	C2	1200	950	850

5. Discussion

5.1. Visualization of results

To enhance the visualization of our results, we have included **Table 4**: Comparison of Jump Height and Peak GRF Among Different Skill Levels. This table provides a clear visual representation of the differences in jump height and peak Ground Reaction Force (GRF) among the advanced, intermediate, and beginner groups.

Table 4. Comparison of jump height and peak GRF among different skill levels.

Group	Skill Level	Average Jump Height (m)	Peak GRF (N)
Advanced	Professional	0.775	1625
Intermediate	University	0.625	1375
Beginner	Amateur	0.525	1150

5.2. Comparison with existing literature

Our findings are consistent with previous studies that have examined the biomechanics of jumping in athletes. For example, Komi [3] highlighted the importance of lower limb muscle strength and the stretch-shortening cycle (SSC) in achieving high jump performance. Our study supports this by demonstrating that advanced athletes, who exhibited superior control of joint angles and higher force output, achieved significantly greater jump heights compared to intermediate and beginner athletes. This aligns with the findings of Bobbert [11], who showed that increased quadriceps and gastrocnemius strength directly contributes to higher jump performance.

Additionally, our results on the impact of joint angles on jump height are in agreement with Aagaard [17], who reported that optimal knee and hip joint angles during takeoff are crucial for maximizing jump height. Our study further extends this by providing detailed kinematic data on joint angles and their correlation with jump performance across different skill levels.

5.3. Limitations of the study

While our study provides valuable insights into the biomechanics of jumping in basketball athletes, there are several limitations that should be acknowledged:

Sample Size and Diversity: Our study included a relatively small sample size of 20 athletes, which limits the generalizability of our findings. Future research should include a larger and more diverse sample, encompassing athletes of different ages, genders, and skill levels to enhance the applicability of the results.

Lack of Long-term Follow-up: The study did not include a long-term follow-up to assess the sustained impact of the proposed training strategies on athlete performance and injury prevention. Longitudinal studies are recommended to evaluate the long-term effectiveness of these interventions.

Cultural and Regional Variability: The study did not account for potential differences among athletes from different cultural and regional backgrounds. Future research should consider multi-center studies to evaluate the universality of the findings across diverse populations.

Economic Feasibility: The study did not conduct a cost-benefit analysis of the proposed training strategies. Future research should include an economic evaluation to assess the feasibility and practicality of implementing these strategies in real-world settings.

5.4. Impact of limitations on conclusions

The limitations identified above may impact the conclusions drawn from this study. The small sample size and lack of diversity may restrict the generalizability of our findings to broader populations. Additionally, the absence of long-term follow-up means that the long-term effects of the training strategies remain uncertain. These limitations highlight the need for further research to validate and expand upon our results.

5.5. Detailed training optimization strategies

Based on the biomechanical analysis and findings from this study, we propose detailed training optimization strategies tailored to athletes of different skill levels. These strategies include specific training cycles, frequency, intensity, and methods for adjusting the training program based on the athlete's progress.

1) Advanced group athletes:

Training goals: Maximize jump height and efficiency through advanced strength training, plyometrics, and technique refinement.

Training cycles:

Cycle duration: 16 weeks, divided into four phases:

Phase 1 (Weeks 1–4): Strength Foundation.

Phase 2 (Weeks 5–8): Power Development.

Phase 3 (Weeks 9–12): Performance Optimization.

Phase 4 (Weeks 13–16): Peaking and Tapering.

Frequency:

Strength training: 3 sessions per week.

Plyometric training: 2 sessions per week.

Technique refinement: 1 session per week (video analysis and feedback)

Intensity:

Strength training: 75–85% of 1RM for major lifts (e.g., squats, deadlifts, lunges).

Plyometric training: High-intensity exercises (e.g., depth jumps, box jumps, hurdle hops) with 3–4 sets of 6–8 reps.

Technique refinement: Focus on optimizing joint angles and movement patterns.

Adjustments:

Progress monitoring: Weekly assessments of jump height, GRF, and joint angles.

Adjustments: Increase load or intensity based on progress. If performance plateaus, introduce new exercises or adjust training volume. Ensure adequate recovery to prevent overtraining.

2) Intermediate group athletes:

Training goals: Improve jump performance through targeted strength and plyometric training, with a focus on technique improvement.

Training cycles:

Cycle duration: 12 weeks, divided into two phases:

Phase 1 (Weeks 1–6): Strength and Technique Development.

Phase 2 (Weeks 7–12): Power and Performance Improvement.

Frequency:

Strength training: 2 sessions per week.

Plyometric training: 2 sessions per week.

Technique refinement: 1 session per week (video analysis and feedback).

Intensity:

Strength training: 60–75% of 1RM for major lifts (e.g., goblet squats, lunges, leg press).

Plyometric training: Moderate-intensity exercises (e.g., single-leg hops, bounding, box jumps) with 2–3 sets of 8–12 reps.

Technique refinement: Focus on improving joint angle control and force output efficiency.

Adjustments:

Progress monitoring: Bi-weekly assessments of jump height, GRF, and joint angles.

Adjustments: Gradually increase intensity and complexity of exercises based on progress. Introduce new drills to address specific weaknesses. Ensure adequate recovery and adjust training intensity based on feedback.

3) Beginner group athletes:

Training goals: Develop foundational strength and basic jumping technique to enhance overall performance.

Training cycles:

Cycle duration: 12 weeks, divided into two phases:

Phase 1 (Weeks 1–6): Introduction to Strength and Technique.

Phase 2 (Weeks 7–12): Improvement and Skill Development.

Frequency:

Strength training: 2 sessions per week.

Plyometric training: 1 session per week.

Technique refinement: 1 session per week (video analysis and feedback).

Intensity:

Strength training: Bodyweight exercises and light resistance (e.g., goblet squats, lunges, resistance band exercises).

Plyometric training: Low-intensity exercises (e.g., jump rope, basic box jumps, double-leg hops) with 2 sets of 10–15 reps.

Technique refinement: Focus on basic movement patterns, joint stability, and proper landing mechanics.

Adjustments:

Progress monitoring: Monthly assessments of jump height, GRF, and joint angles.

Adjustments: Gradually increase load and intensity based on progress. Provide continuous feedback to correct technique and improve performance. Ensure adequate recovery and adjust training volume based on athlete feedback.

For all groups, incorporating mental training and recovery plans (e.g., sleep and nutrition guidance) is recommended to enhance overall performance. Additionally, a cost-benefit analysis of the proposed training strategies should be conducted to assess their economic feasibility.

To enhance the generalizability of the findings, future studies should include a broader range of athletes (e.g., different ages, genders, and skill levels). Long-term follow-up studies are also recommended to evaluate the sustained impact of the proposed training strategies on athlete performance and injury prevention.

5.6. Long-term follow-up study design

The current study provides valuable insights into the biomechanics of jumping and the immediate effects of training optimization strategies on basketball athletes. However, it lacks a long-term follow-up component, which is essential for evaluating the sustained impact of these strategies on athletes' performance and health. To address this gap, we propose a detailed plan for a long-term follow-up study.

1) Long-term follow-up study design

Study Duration and Phases.

Duration: The proposed long-term follow-up study will span 3–5 years to capture the long-term effects of training interventions.

Phases: Initial Assessment Phase (Year 1): Baseline measurements of biomechanical parameters, performance metrics, and health indicators.

Intervention Phase (Years 1–3): Implementation of training optimization strategies tailored to different skill levels and demographics.

Follow-up Phase (Years 3–5): Periodic assessments of performance, biomechanics, and health outcomes to evaluate the sustained impact of the training interventions.

2) Participant recruitment and cohort design

Recruitment: Athletes from the original study will be invited to participate in the long-term follow-up, along with new recruits to ensure a diverse and representative sample.

Cohort Design: The study will include athletes of different ages, genders, and skill levels to assess the generalizability of the findings.

3) Data collection and monitoring

Biomechanical Assessments: Regular use of motion capture systems and force plates to monitor changes in jumping biomechanics over time.

Performance Metrics: Periodic evaluation of jump height, speed, agility, and other relevant performance indicators.

Health Indicators: Monitoring of injury rates, recovery times, and overall health status through medical assessments and self-reported surveys.

Training Logs: Collection of detailed training logs to track adherence to the training programs and any modifications made over time.

4) Statistical analysis and reporting

Longitudinal Data Analysis: Use of mixed-effects models and repeated-measures ANOVA to analyze changes in performance and health indicators over time.

Subgroup Analyses: Examination of differences based on age, gender, and skill level to identify specific trends and adaptations.

Reporting: Regular publication of interim and final reports to disseminate findings and provide insights into the long-term effectiveness of training strategies.

5) Ethical considerations

Informed Consent: Obtain informed consent from all participants, ensuring they understand the long-term nature of the study and their rights to withdraw at any time.

Data Privacy: Ensure the confidentiality and security of participant data throughout the study period.

6) Impact of long-term follow-up

A long-term follow-up study will provide critical insights into the sustained effects of training optimization strategies on athletes' performance and health. This approach will:

Evaluate Long-term Adaptations: Assess how biomechanical changes translate into long-term performance improvements.

Monitor Health Outcomes: Identify potential risks and benefits associated with the training interventions over an extended period.

Inform Future Training Programs: Provide evidence-based recommendations for the development of sustainable and effective training strategies.

6. Summary

This study proposes training optimisation strategies for athletes of different skill levels through biomechanical analyses of basketball players' jumping movements. The results of the study show that athletes' jump height and efficiency can be significantly improved through precise adjustment of joint angles, enhancement of lower limb strength, and optimisation of jumping technique. In addition, the study highlights the importance of scientific training methods in reducing injury risk and enhancing athletic performance.

1) Joint angles and power output: The study found that high-level athletes were able to better control knee, hip and ankle joint angles during the jump and demonstrated higher power output and better cushioning. This enabled them to achieve jump heights in excess of 0.75 m, compared to 0.6–0.65 m and 0.5–0.55 m for intermediate and junior athletes, respectively.

2) Training optimisation strategies: specific training plans are proposed for athletes of different skill levels, including training cycles, frequency, intensity and recovery strategies. These plans aim to enhance jumping performance by building strength, optimising technique and improving motor control.

3) Individualised adjustments: the study highlights the importance of adjusting training plans based on athletes' feedback and progress. By regularly evaluating and adjusting training components, the scientific validity and effectiveness of training programmes can be ensured.

The training optimisation strategies proposed in this study provide scientific guidance for basketball training and help athletes transition from basic to advanced levels. By implementing these strategies, coaches can more effectively improve athletes' jumping ability while reducing the risk of injury. In addition, the study recommended that future research should further explore the economic feasibility and long-term effects of training programmes to ensure the sustainability of these strategies in practical application.

In conclusion, the present study not only revealed the key biomechanical factors affecting jumping performance in basketball players, but also provided a theoretical basis for the development of individualised training programmes. Through scientific training methods and continuous monitoring and adjustment, athletes can significantly improve their jumping ability and thus achieve better performance in the game.

Author contributions: Conceptualization, GD and DW; methodology, XZ; software, GD; validation, GD, DW and XZ; formal analysis, DW; investigation, DW; resources, XZ; data curation, XZ; writing—original draft preparation, GD; writing—review and editing, DW; visualization, GD; supervision, XZ. All authors have read and agreed to the published version of the manuscript.

Ethical approval: Not applicable.

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

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